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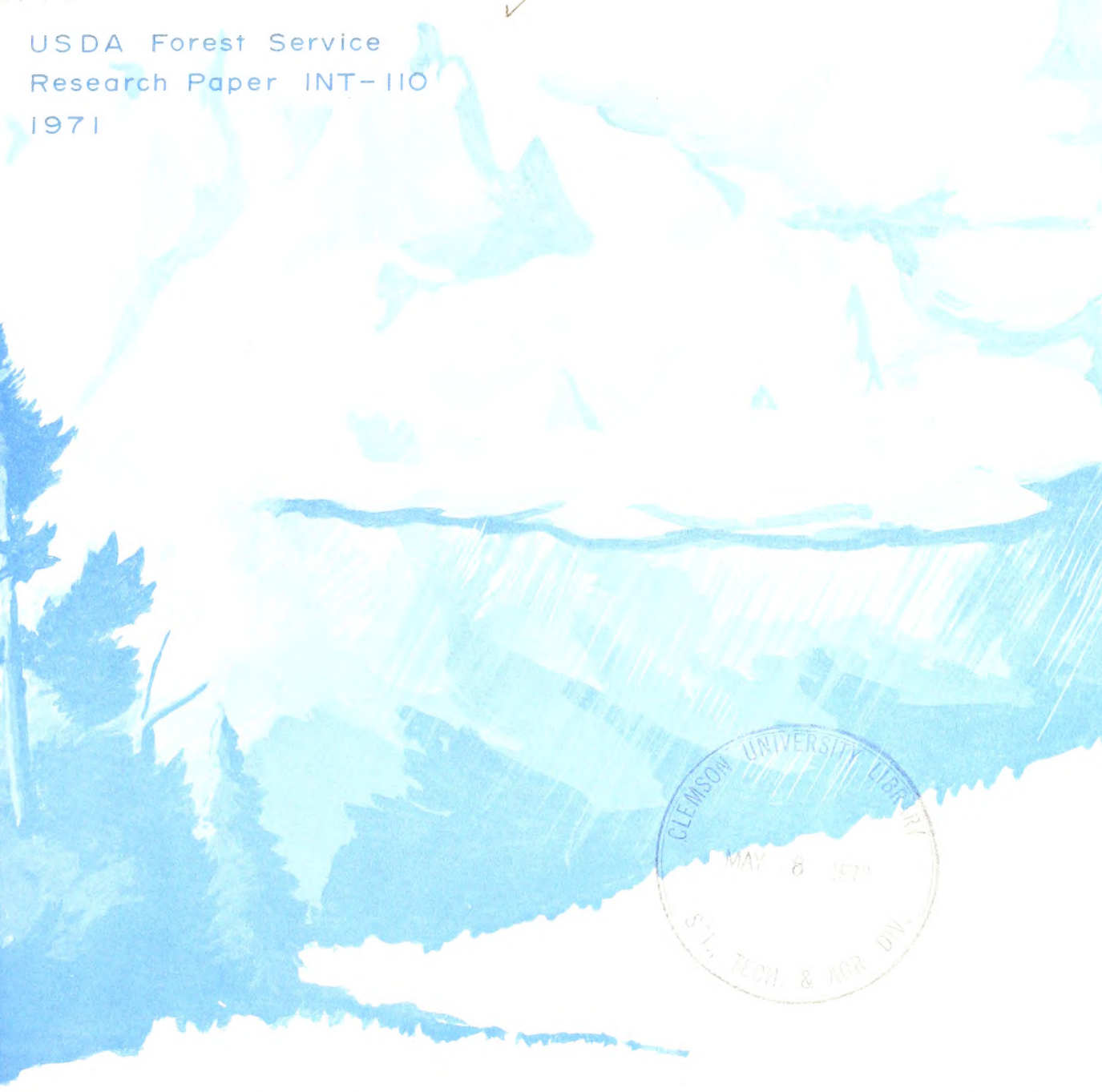

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PRECIPITATION CHARACTERISTICS OF SUMMER STORMS at high-elevation stations in Utah

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
OGDEN, UTAH 84401

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PRECIPITATION CHARACTERISTICS OF SUMMER STORMS AT HIGH-ELEVATION STATIONS IN UTAH

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ABSTRACT

This paper presents the results of data analyses for 25 precipitation intensity stations on two study areas in central and north-central Utah located at elevations between 4,350 and 10,150 feet m.s.l. All data were collected during the period May 1 to October 31. Each station has 10 or more years of record; one station has 30 years of record. The following analyses were made: (1) Record consistency; (2) definition of local precipitation zones; (3) intensity-duration-frequency characteristics; (4) 24-hour depths; (5) monthly depths and number of storms; (6) storm occurrence by hour of the day; and (7) storm occurrence by storm duration. The precipitation zone between 6,500 and 8,000 feet m.s.l. is expected to receive the greatest rainfall intensities. There is a trend toward reduced intensities with increasing elevation but the trend is not uniform. However, those precipitation zones that receive the most intense rainfall do not coincide with those zones receiving the greatest depth of rainfall. Generally, rainfall depth increases with elevation, but on one study area the zone that received the greatest depth was not the highest elevation zone. A marked difference in the distribution of storm occurrence by hour between the two study areas is attributed to differences in storm type and to differences in the principal source of summer moisture. Average storm length varies inversely with elevation.

INTRODUCTION

Hydrologists commonly accept the fact that rainfall records for high mountain areas are exceedingly scanty. In Utah, most of the rainfall intensity gages are located in the valleys, at elevations less than 6,000 feet m.s.l. Most of the records of rainfall in the valleys have never been analyzed for precipitation characteristics of storms having durations of less than 60 minutes. Even the available records of rainfall in the mountains have never been analyzed for those storm characteristics that are most pertinent to wildland managers and research workers in the field of watershed protection. In fact, most of the available records have never been analyzed beyond weekly or monthly totals.

This paper presents the results of analyses of data from two mountain networks of recording precipitation gages: 11 stations on the Great Basin Experimental Area in central Utah; and 14 stations on the Davis County Experimental Watershed in northern Utah. The gages in central Utah are located at elevations between 5,550 and 10,150 feet m.s.l. The gages in northern Utah are located at elevations between 4,350 and 9,000 feet m.s.l. (figs. 1 and 2).

All of the rainfall records were collected during the period May 1st to October 31st. Most of these records were obtained from weighing-type analog gages, but a few of the earliest records were from tipping-bucket gages. The total records of all stations comprise 495 station seasons; 5,207 station storms were recorded. A single storm was often recorded on more than one gage.

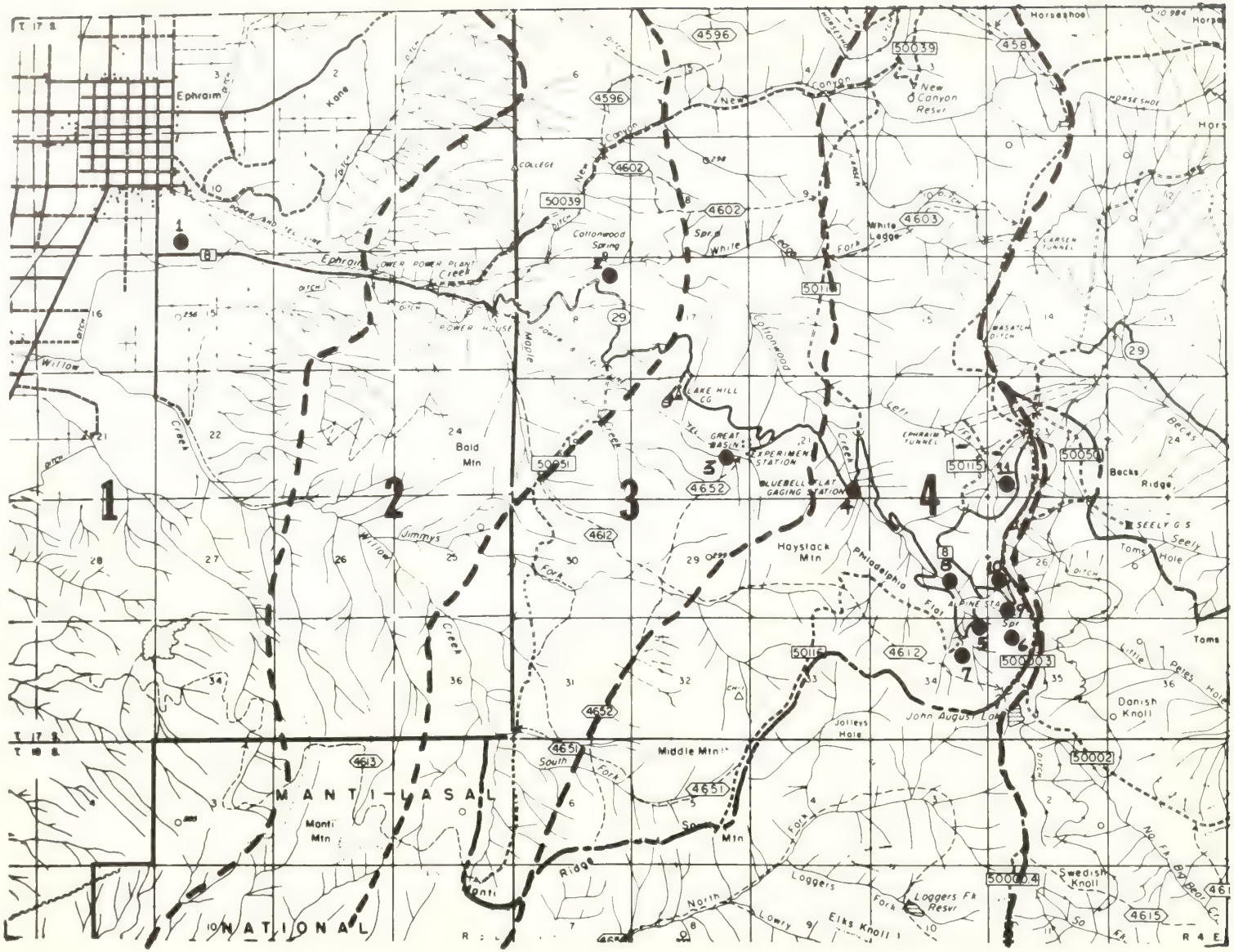

Figure 1.--Map of the Great Basin Experimental Area. The numbered solid circles are precipitation intensity gages. The four precipitation zones are delineated with heavy dashed lines.

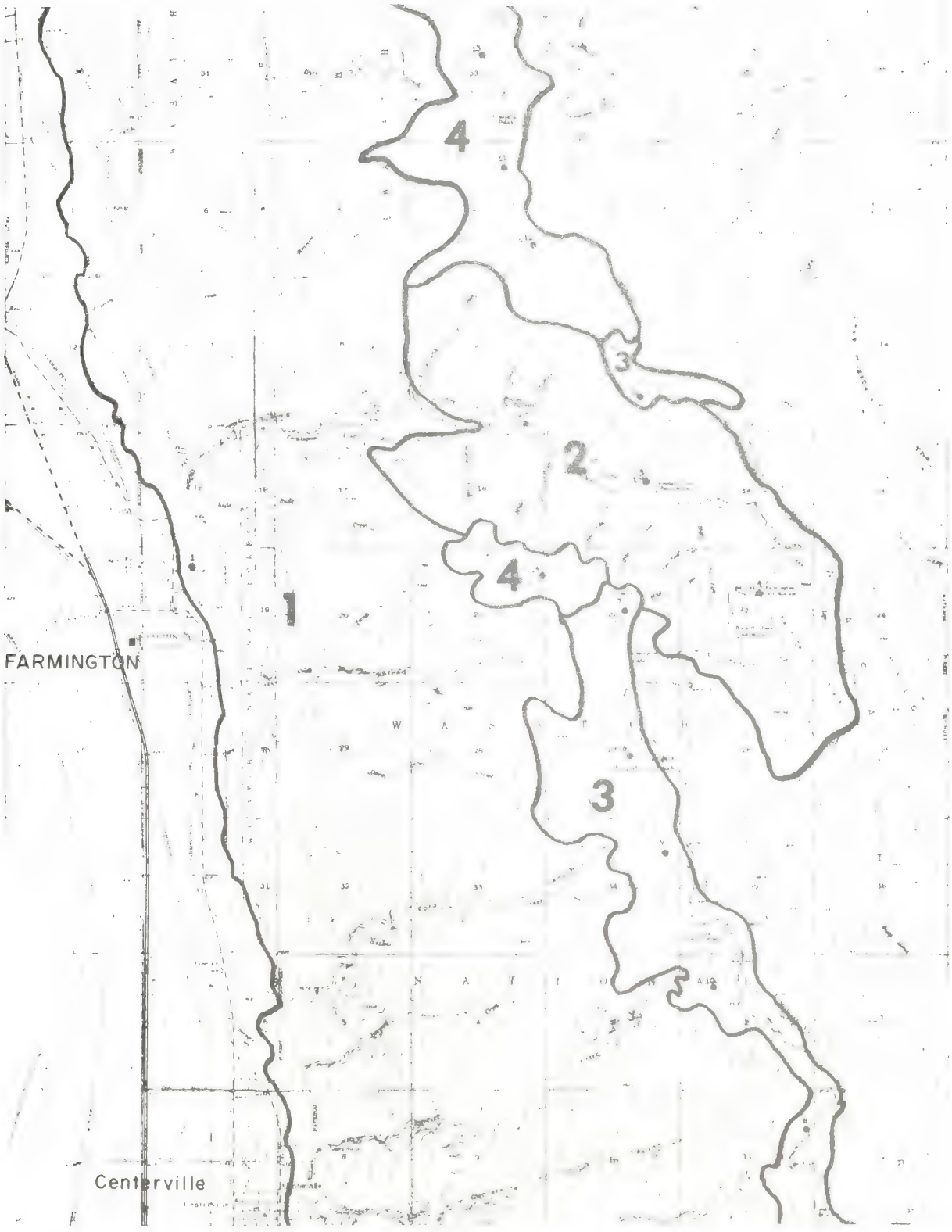

Figure 2.--Map of [illegible] are precipitation intensity gages. The four precipitation zones are delineated with heavy solid lines.

The Davis County Experimental Watershed and the Great Basin Experimental Area are located on the Wasatch Range and the Wasatch Plateau, respectively. These two mountain ranges form the high-elevation midrib of the northern two-thirds of the State of Utah. The Wasatch Range forms the northern half of this midrib and is characterized by steep slopes, deep canyons, and ridges that rise to about 12,500 feet m.s.l.--some 3,000 to 6,000 feet above the adjacent valleys. The high-plateau section of the Colorado Plateau province extends southward from the Wasatch Range to form the southern half of this midrib. The Wasatch Plateau extends 75 miles from north to south and has a very narrow summit, usually less than 6 miles wide. The western front is a great monoclinal flexure whose strata bend upward to the summit in a single sweep. The summit is about 10,500 feet m.s.l.--some 4,000 to 5,500 feet above the San Pitch Valley to the west. The rim of the plateau has been notched by erosion and the streams have trenched back toward the summit giving the plateau a dissected appearance.

These two mountain ranges have a relatively long history of land use--particularly grazing--dating back to about 1847. Summer convective storms delivering very high-intensity rainfall have been the source of destructive debris floods. Summer debris floods emanating from the Wasatch Range were particularly destructive (Bailey et al. 1934; and Bailey et al. 1947). These summer-flood flows took lives, destroyed property, and disrupted communities.

On both mountain ranges, summer precipitation contributes very little to streamflow. However, it is important to the production of mountain vegetation that is vital to soil stability (Packer 1951; Orr 1957; Packer 1963; and Croft and Bailey 1964). However, vegetal cover is only one factor that affects the hydrologic performance of a watershed. Storm characteristics also have a major effect on the processes of soil erosion and flood production, especially when the land becomes barren of vegetal cover due to fire, road construction, overgrazing, or urban development.

A storm was defined for this study as a period of precipitation, uninterrupted for a period exceeding 1 hour, delivering at least 0.10 inch of water. Most of these storms were convective thunderstorms and frontal thunderstorms aided through orographic lifting. Summer convective cells, often associated with lightning, usually approach from the south or southwest, which is the direction of the prevailing wind of that season. Some of the storms that delivered the greatest intensity of rainfall were probably of a type that has been termed orographic-convective. The primary source of summer moisture aloft comes from the Gulf of Mexico (Humphrey 1962). A small proportion of the total storms comes from large frontal systems.

METHODS

Manual and machine methods were used to digitize the original analog rainfall records. Compilation of the digitized record was done by computer.[1] The final computer output for every storm consisted of both accumulated precipitation depth and rainfall intensity for the following 12 time durations: 2, 5, 10, 15, 20, and 30 minutes and 1, 2, 4, 6, 12, and 24 hours. The computer output also included the total precipitation depth for every month as well as a yearly summary of maximum depth and intensity.

Record Consistency

All of the records were checked for consistency by double-mass plotting (Searcy and Hardison 1960). This technique was applied to the combined depth records only for July and August because all of the gages were in operation during these 2 months. A three-station preliminary base pattern for each study area was arbitrarily selected to which all other stations were compared. From these comparisons, the three most consistent stations were then chosen as the final base pattern.

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[1]Appreciation is expressed to Leon Huber and Jack W. Homeyer of Utah State University and the Intermountain Forest and Range Experiment Station, respectively. Mr. Huber is author of the computer program PREINT; Mr. Homeyer authored the computer program ANADIG. These programs contributed materially to the completion of this work.

Frequency Analysis

A detailed annual series frequency analysis of rainfall intensity was made for every station. A separate analysis was made for each of the 12 time durations. The formula developed by Weibull was used to obtain plotting positions (Chow 1964).

$$T = \frac{n+1}{m}$$

where

T = recurrence interval, years
n = number of years of record
m = order number of the items arranged in descending order.

This formula has been found to be theoretically suitable for plotting annual maximum series on extremal distribution paper (Chow 1953). However, the data in this study were more nearly straight on extremal log paper.

Precipitation Zones

Peck and Brown (1962) divided Utah into 20 precipitation regions. They found that a large amount of the variation between regions in the May-September precipitation was accounted for by elevation. All of our data are point data. Consequently, we had to define criteria for dividing the study areas into homogeneous zones in order to make areal application of these point data.

The three criteria used follow: (1) station elevation; (2) the values from the station intensity-duration-frequency curve; and (3) the station I_{10}/I_2 ratio for all durations between 2 and 30 minutes (figs. 1 and 2, tables 1 and 2). The latter is a dimensionless ratio that expresses the average slope of the short-duration rainfall intensity curves between 2 and 10 years. This ratio was computed by dividing the summation of intensities having durations of 2, 5, 10, 15, 20, and 30 minutes for the 10-year recurrence interval by the comparable summation for a recurrence interval of 2 years. Any region that is homogeneous with respect to its rainstorm characteristics should have frequency curves of about equal slope or steepness. Consequently, the I_{10}/I_2 ratio is a useful statistic for comparing the slopes of frequency curves as a basis for judging homogeneity of precipitation zones.

24-Hour Precipitation Depth

The intensities for the 24-hour duration were converted to precipitation depths for recurrence intervals of 10, 25, and 50 years. Twenty-four hours was the longest duration examined in this study.

Average Monthly Depth and Number of Storms

Analyses for the average monthly depth of precipitation and the average number of storms per month are complete only for June-September. At the highest elevation stations, the data for May and October were insufficient to compute a reliable monthly average.

Storm Occurrence by Hour

Storm occurrence by hour was analyzed by compiling the number of storms starting in any hour of the day expressed as a percent of the total storms. These data were plotted as a mass curve for each zone.

Storm Occurrence by Storm Duration

In each zone, 11 duration intervals were established to examine the relationship between storm occurrence and storm duration: 1-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-90, 91-120, 121-240, 241-360, and greater than 360 minutes. The number of storms that occurred in each duration interval was totaled. A mass curve of percent of total storms was plotted against the central value, or "class mark," of each duration interval. These zonal curves are unweighted averages.

Table 1.--*Listing of the precipitation intensity stations*

Station	Map number[1]	Zone number	Period of record	Years of record	Station elevation
DAVIS COUNTY EXPERIMENTAL WATERSHED					
Farmington Warehouse	1	1	1939-68	30	4,350
Sunset	2	2	[2]1948-65	17	6,400
Rice Climatic Station	3	2	1942-68	27	6,800
Farmington Flat	4	2	1942-65	24	7,600
Head Bigler Creek	5	3	1941-66	26	8,000
Centerville	8	3	[2]1948-58	10	8,200
Parrish Climatic Station	10	3	1942-63	22	8,200
Head Miller Creek	14	4	1941-62	22	8,350
Mud Creek	7	3	1939-58	20	8,370
Head Ford Creek	9	3	1946-62	17	8,700
Steed Creek	6	3	1946-62	17	8,800
Bairs Canyon	13	4	1947-57	11	8,800
Head Halfway Creek	12	4	1941-66	26	8,900
Head Sheppard Creek	11	4	1948-57	10	9,000
GREAT BASIN EXPERIMENTAL AREA					
Sorenson's Field	1	1	1946-65	20	5,550
Oaks Climatic Station	2	2	1942-65	24	7,650
GBRS Headquarters	3	3	1937-65	29	8,850
Bluebell Bridge	4	4	1942-55	14	9,000
Meadows Climatic Station	5	4	1942-65	24	9,850
Alpine Cattle Pasture	6	4	1946-58	13	9,900
Alpine Physical Factors Station	7	4	[3]1919-43	20	9,900
Philadelphia Flat	8	4	1942-55	14	9,950
Alpine Area A	9	4	1944-65	22	10,100
Left Fork Ephraim Creek #1	11	4	1946-59	14	10,100
Alpine Area B	10	4	1944-65	22	10,150

[1]See figures 1 and 2.
[2]Except 1949.
[3]Except 1921, 1930, 1933, and 1934.

Table 2.--*Precipitation zones for each study area*

Precipitation zone	Average station elevation	Zonal I_{10}/I_2	Vegetal type
	DAVIS COUNTY EXPERIMENTAL WATERSHED		
1	4,350	1.87	Oakbrush
2	6,930	1.94	Aspen-fir[1]
3	8,380	2.30	Spruce-fir[2]
4	8,760	2.49	Spruce-fir
	GREAT BASIN EXPERIMENTAL AREA		
1	5,550	2.35	Pinyon-juniper
2	7,650	3.16	Oakbrush
3	8,850	1.73	Aspen-fir
4	9,850	2.25	Spruce-fir

[1]The lower limits of this precipitation zone are in the oakbrush type.

[2]The lower limits of this precipitation zone are in the aspen-fir type.

RESULTS

Consistency Test

The records were not adjusted. None of the mass curves plotted as smooth straight lines and isolated points fluctuated both above and below the trend line. Even so, the breaks in the lines didn't persist for a period as long as 5 years. The breaks in the lines were considered to be no greater than might reasonably be expected for thunderstorm data obtained from mountainous areas.

Precipitation Zones

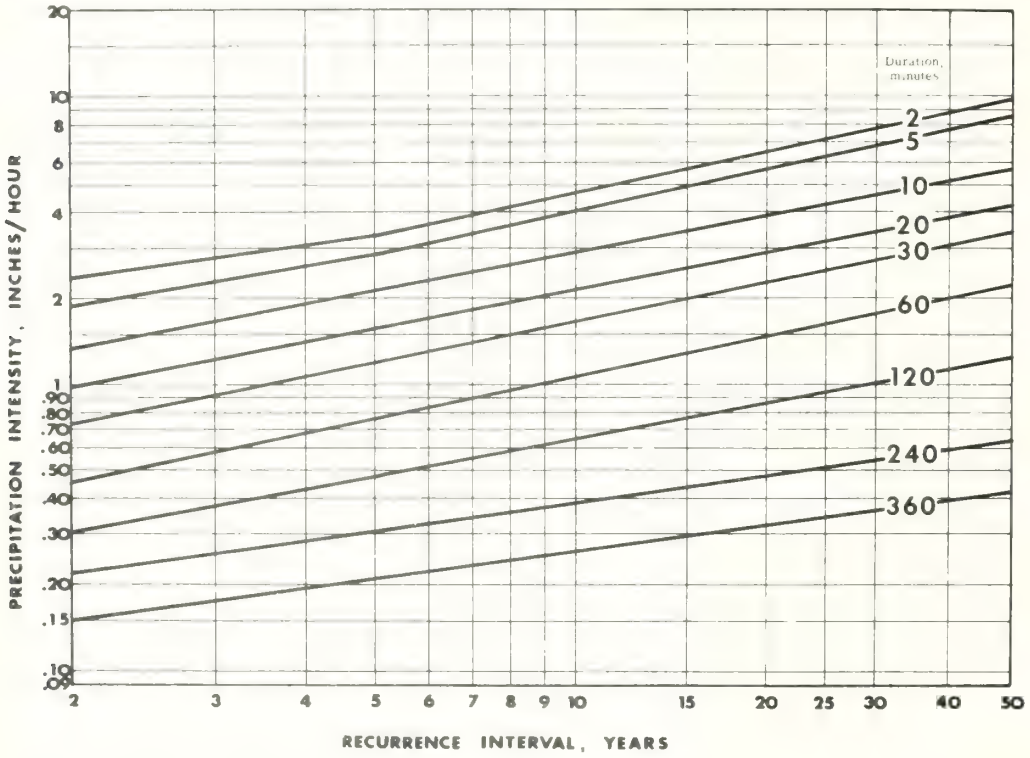
Within each study area, vegetal patterns were closely related to the four precipitation zones (table 2). This was not unexpected; however, vegetal types were not considered when the precipitation zones were established. On the Wasatch Plateau, the major vegetal types are pinyon-juniper, oakbrush, aspen-fir, and spruce-fir. On the Wasatch Range, the pinyon-juniper type disappears and oakbrush occupies sites similar to those occupied by pinyon-juniper in areas south of the Wasatch Range.

Intensity-Duration-Frequency Characteristics

The curves in figures 3a to 3d and 4a to 4d are for recurrence intervals of 2 to 50 years and storm durations of 2, 5, 10, 20, and 30 minutes and 1, 2, 4, and 6 hours. The 50-year return period intensity is a linear extrapolation and as such must be used with caution. The 10-year intensity is expected to be accurately determined because one or more stations in the eight precipitation zones have records dating back more than 20 years. All of the curves were fitted by eye (Dalrymple 1960). In reading them, it is important to remember that the recurrence interval is the average interval in which an intensity of given duration will recur as an annual seasonal maximum.

Figure 3.--Intensity-duration-frequency curves for recurrence intervals of 2 to 50 years and durations of 2 minutes to 6 hours for the Davis County Experimental Watershed. Curves for precipitation Zone 1 are shown in 3a, Zone 2 in 3b, Zone 3 in 3c, and Zone 4 in 3d. (Log-extreme distribution)

A



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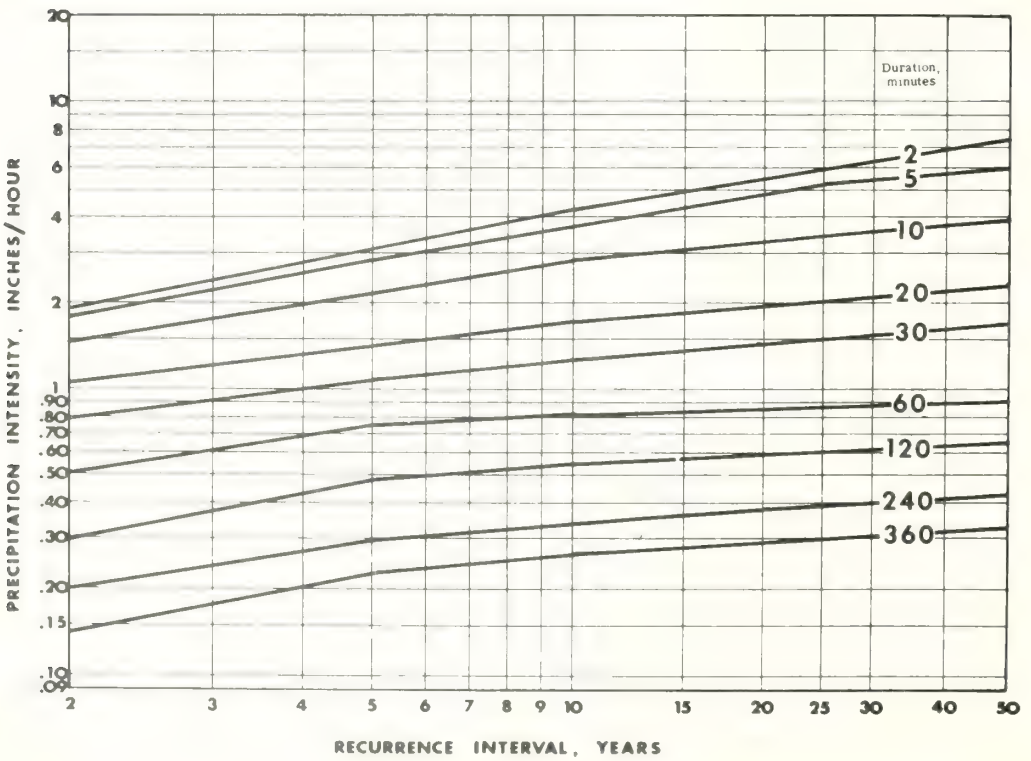

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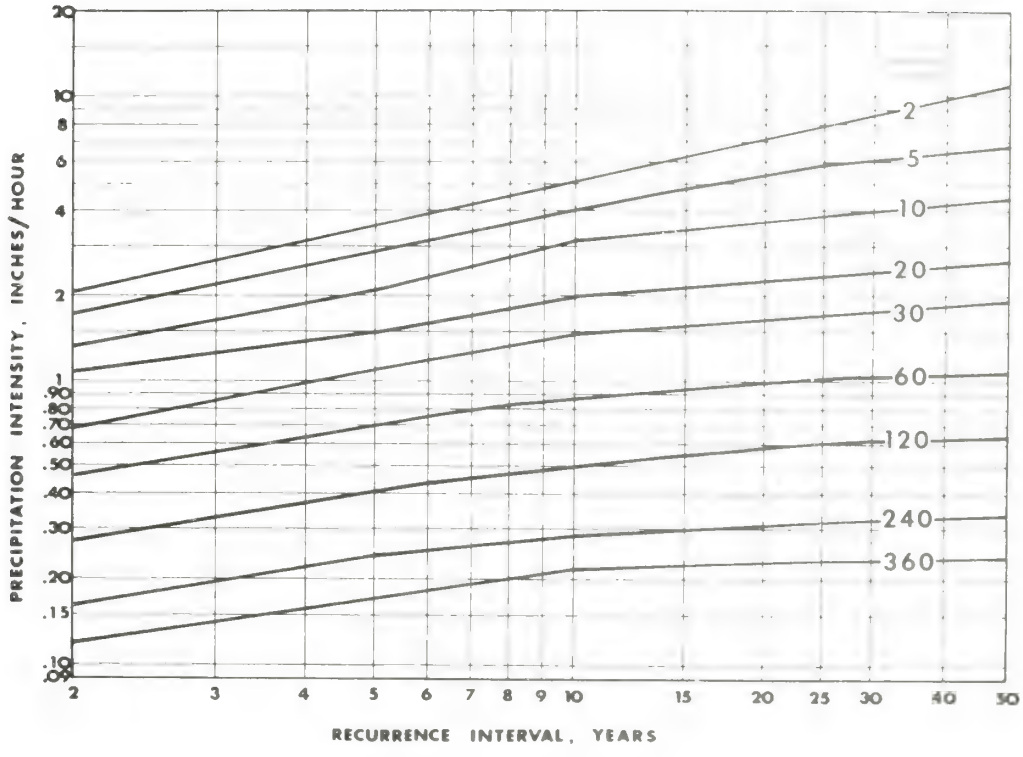
PRECIPITATION INTENSITY, INCHES/HOUR
RECURRENCE INTERVAL, YEARS
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D

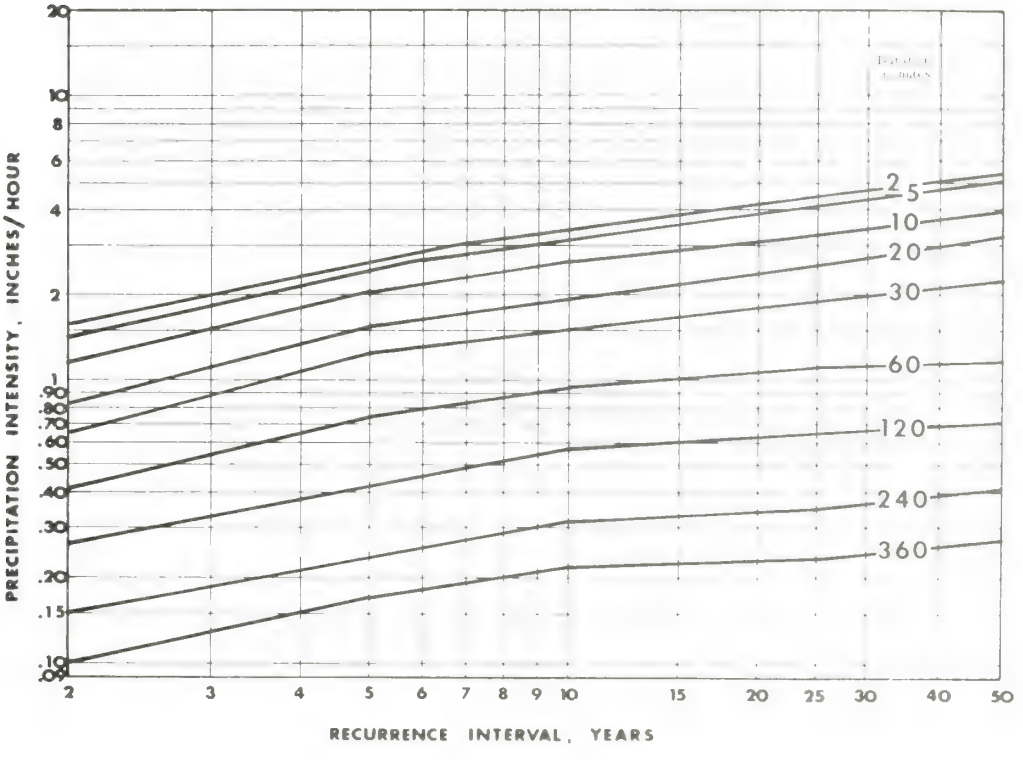
PRECIPITATION INTENSITY, INCHES/HOUR
RECURRENCE INTERVAL, YEARS
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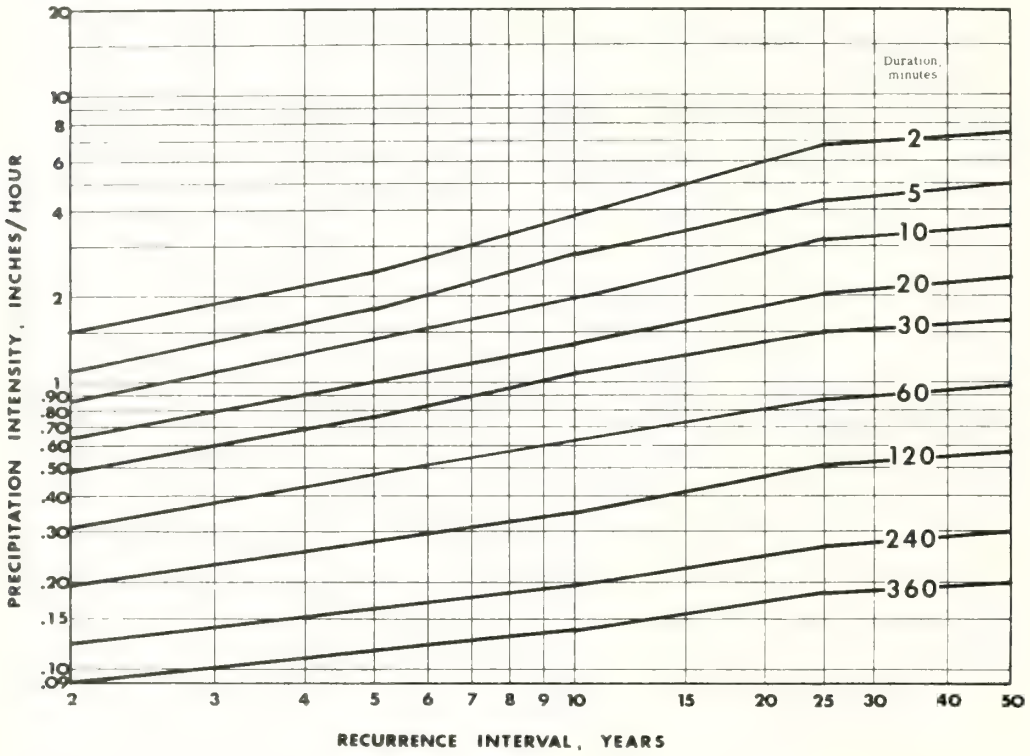
Figure 4.--Intensity-duration-frequency curves for recurrence intervals of 2 to 50 years and durations of 2 minutes to 6 hours for the Great Basin Experimental Area. Curves for precipitation Zone 1 are shown in 4a, Zone 2 in 4b, Zone 3 in 4c, and Zone 4 in 4d. (Log-extreme distribution)

A



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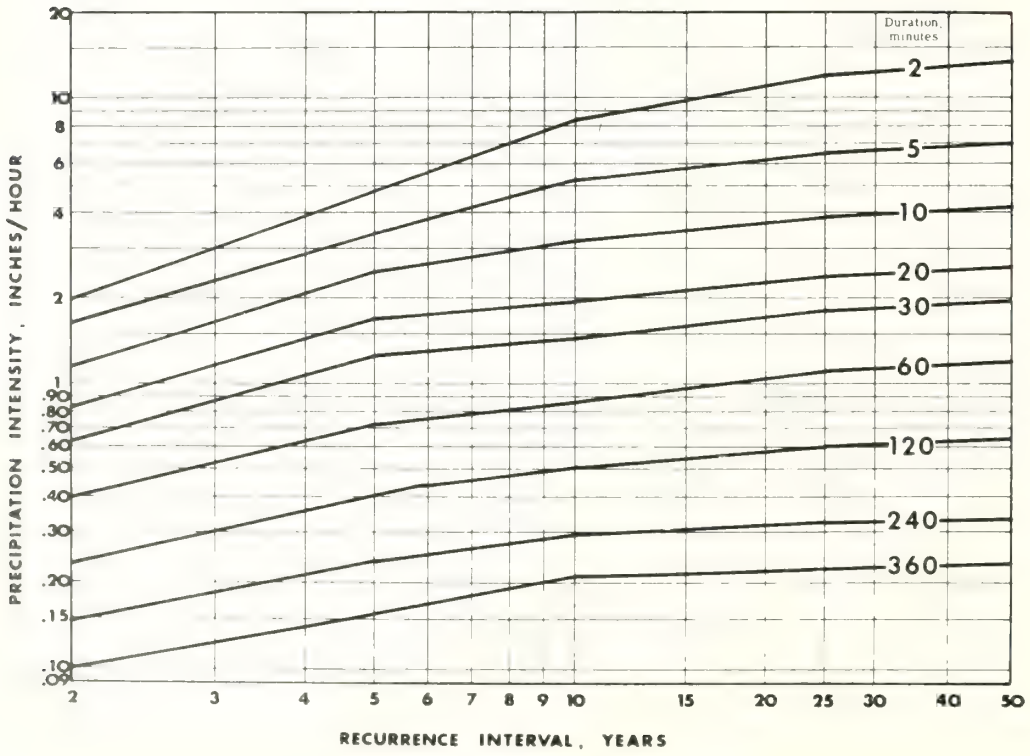

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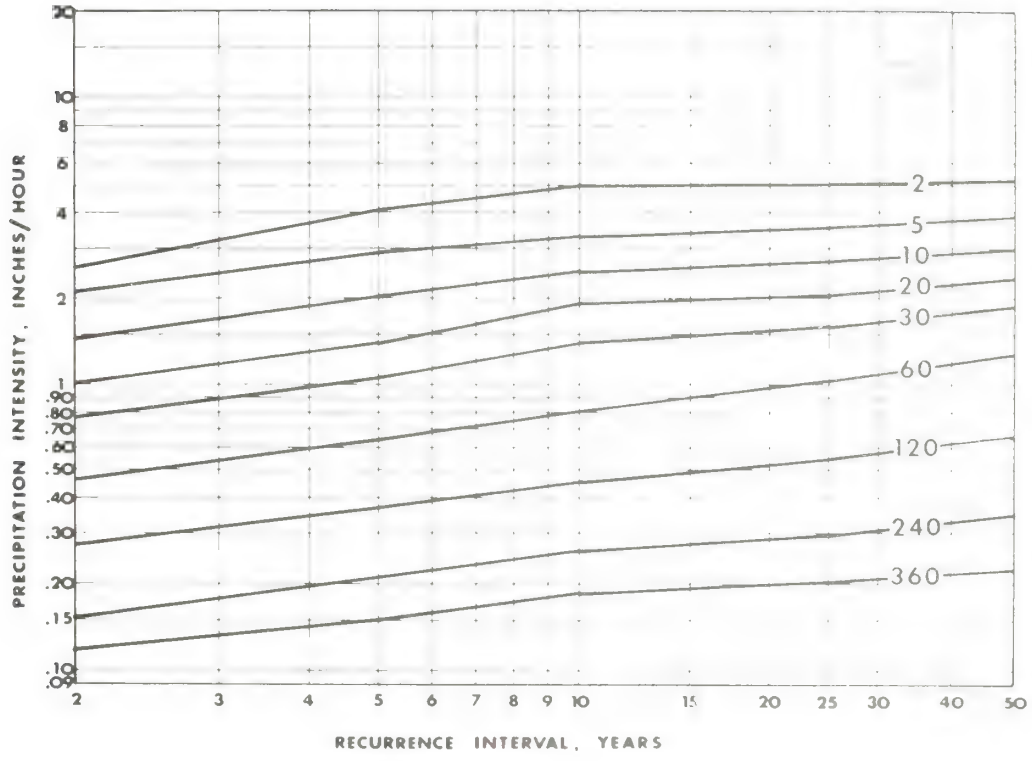
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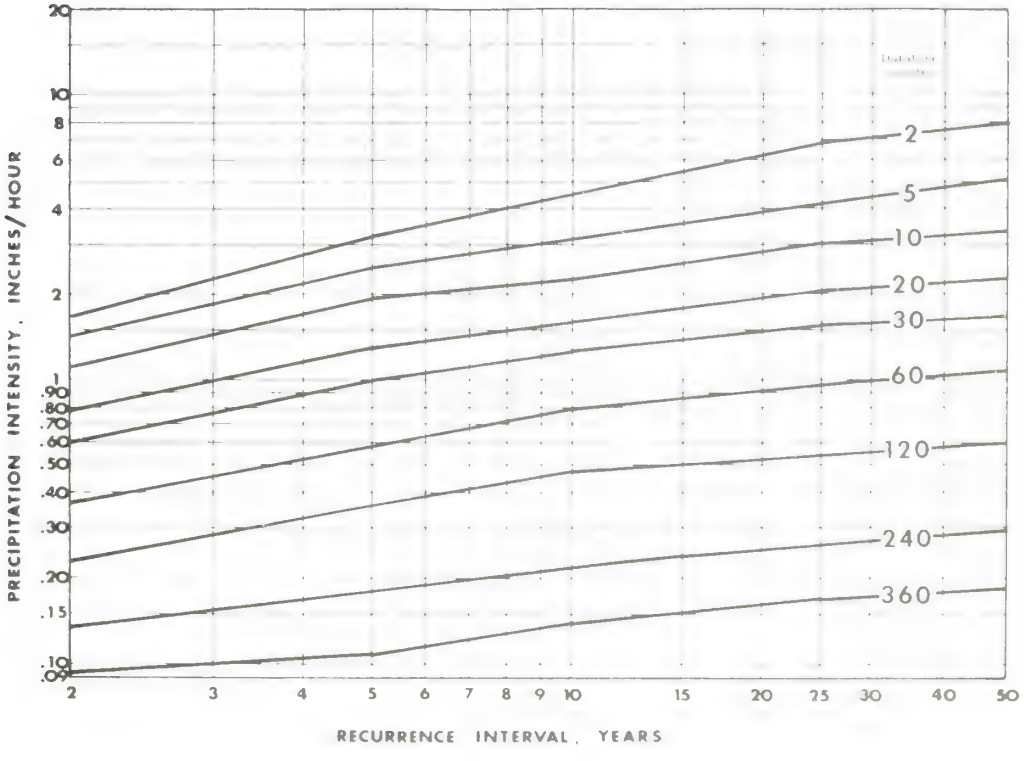
PRECIPITATION INTENSITY, INCHES/HOUR
RECURRENCE INTERVAL, YEARS
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The precipitation values used in making the zonal curves contained some snowfall events. At the higher elevations, snow has been recorded during every month of the year. However, there is little doubt that the values for periods of 2 hours and shorter for recurrence intervals of 10 years and longer are rainfall events.

Close examination of figures 3 and 4 reveals that generalized comparisons are difficult to make. Comparisons should be confined to specific durations and recurrence intervals because the magnitude of the 2-year intensity and the slope of the curves vary within and between zones. For instance, on the Davis County area the expected 20-minute, 50-year intensity is greatest in Zone 1, while the 20-minute, 2-year intensity is greatest in Zone 3.

Zone 2, aspen-fir type, in the Davis County area occupies the bottom of the higher reaches of Farmington Canyon. All of this zone lies behind a topographic barrier with respect to the prevailing southwest storm direction, and is the only zone on the leeward slope. The physiographic effect in Zone 2 was not determined precisely; however, compared to Zones 1 and 3, it appears that for durations less than 2 hours the expected intensities decrease--especially at long recurrence intervals.

On both study areas, as elevation increases, there is a trend toward reduced intensities at the longer recurrence intervals. However, this trend is not uniform. On each area maximum expected intensities are usually found in the precipitation zone occupied by the oakbrush type. Fortuitously, this vegetal type also offers good protection against raindrop impact and overland flow.

Expected rainfall intensities in the aspen-fir type on both study areas are somewhat less than those in the oakbrush type at most durations and recurrence intervals, except at the short durations with short recurrence intervals. This exception is probably due to the increased frequency of storm occurrence with increasing elevation. The intensity-duration-frequency curves representative of the higher spruce-fir zone are more steeply inclined than those of the aspen-fir type. In both zones the expected rainfall intensities at short recurrence intervals are about the same, but they are usually greater at the long recurrence intervals in the spruce-fir type. However, the expected intensities in this type are usually less than those in the oakbrush type. On the Davis County Experimental Watershed, Zone 4 in the spruce-fir type is not markedly different from Zone 3, also in the spruce-fir type, except that the 2-minute duration values differ only slightly from the 5-minute values.

24-Hour Depths

Only a small percentage of storms that occur on either study area have durations greater than 6 hours. However, these storms are of interest in the design of contour trenches and road-drainage devices. Storms of long duration are rarely flood-producing events in these areas. Croft and Marston (1950) indicate that the greatest storms on the Davis County Experimental Watershed averaged much less than 6 hours; they ranged from 30 minutes to 10-1/2 hours.

The intensities were converted to depths because depth is of more interest than intensity at the 24-hour duration. The recurrence intervals shown in table 3 are the average intervals in which the given depth will recur as an annual seasonal maximum.

Monthly Precipitation Depth and Number of Storms

The monthly precipitation depths were determined from gage catch. We hoped that these data could clarify the mountain-valley precipitation relationships when used in conjunction with intensity-duration-frequency characteristics.

Table 3.--*Expected annual seasonal maximum 24-hour precipitation depths, in inches, by recurrence intervals and precipitation zones*

Zone	Recurrence interval (years)		
	10	25	50
DAVIS COUNTY EXPERIMENTAL WATERSHED			
1	2.21	2.54	2.74
2	2.04	2.38	2.45
3	1.44	1.87	2.11
4	1.54	1.87	1.97
GREAT BASIN EXPERIMENTAL AREA			
1	1.15	1.50	1.34
2	1.49	2.16	2.47
3	1.70	2.16	2.33
4	1.39	1.66	1.70

Monthly precipitation fluctuates widely between zones and between years. Any month during the period May-October may be completely dry at one or more stations. Also, any month may exceed the average by 300 to 700 percent.

On both study areas, the average number of storms per month tends to vary as does the monthly precipitation depth (table 4). The catch of summer precipitation in Zone 2 on the Davis County Experimental Watershed was relatively high; this was attributed to its leeward position. Hovind (1965) reported similar results, specifically, that gage catch in the lee of a mountain peak exceeded that on the windward slope by as much as 400 percent.

With respect to the zonal intensity-duration-frequency characteristics, the most intense rainfalls do not occur in the precipitation zones receiving the greatest depths of rainfall. The most intense rainfall is generally expected to occur in Zone 2 on the Great Basin Experimental Area and in Zone 1 of the Davis County Experimental Watershed. The depth of expected rainfall on these zones is less than that on one of the higher elevation zones.

No pronounced dry summer period occurs in the Great Basin area. Price and Evans (1937) found a bimodal dry season in June and September. On the other hand, our analysis shows that July and September are the driest months. Considering the random nature of summer precipitation our results are not in serious conflict with those reported by Price and Evans. On the Davis County Experimental Watershed, July is the driest month, and September is the second driest month. The difference in July totals between the two study areas appears to be related to a lesser effect from convective-orographic storms in the Davis County area. Whether this difference on the two areas is primarily due to the greater distance of the Davis County area from the Gulf of Mexico, to a lesser frequency of favorable circulation, or to more intervening mountain barriers that impede the moist southerly flow, is not evident. Apparently the semi-monsoon circulation that develops over the southwestern United States and makes July one of the wettest months of the year in that region does not affect the Davis County area.

Table 4.--*Average depth of precipitation, in inches, and average number of storms by month and precipitation zone*

Zone	June		July		August		September		Average	
	Depth	No. of storms	Depth	No. of storms	Depth	No. of storms	Depth	No. of storms	Depth	No. of storms
DAVIS COUNTY EXPERIMENTAL WATERSHED										
1	1.36	7.3	.34	2.0	1.07	4.7	.76	4.4	.88	4.6
2	1.94	5.5	.63	2.4	1.21	4.1	1.28	4.0	1.26	4.0
3	1.19	4.7	.50	3.1	1.15	4.8	1.04	4.9	.97	4.4
4	1.35	5.4	.61	3.6	1.10	4.9	.92	4.6	1.00	4.6
Average	1.46	5.7	.52	2.8	1.13	4.6	1.00	4.5	1.03	4.4
GREAT BASIN EXPERIMENTAL AREA										
1	0.60	7.7	0.59	6.4	0.73	8.6	0.79	6.4	0.68	7.3
2	1.53	11.3	1.01	8.2	1.15	9.3	.93	7.3	1.16	9.0
3	1.30	9.4	1.41	11.4	1.62	13.2	1.38	10.3	1.43	11.1
4	2.47	11.0	1.41	10.4	1.48	12.3	.98	8.0	1.58	10.4
Average	1.48	9.8	1.10	9.1	1.24	10.8	1.02	8.0	1.21	9.4

Storm Occurrence by Hour

On the average, the Great Basin area receives more than twice as many storms during the period June-September than does the Davis County area (table 4).

Between the two areas, differences in hour of storm occurrence are much more striking than are zonal differences (figures 5, 6). The inset in each of figures 5 and 6 is a schematic showing the distribution of storms by hour; in each, midnight is adjusted to zero. The insets cannot be used to derive figures 5 or 6.

The curve for the Great Basin area is of the S-type, while that for the Davis County area is more linear--slightly concave upward. Thus, only 13 percent of the storms in the Great Basin area occur before 0600 hours, 45 percent before 1200 hours, and 84 percent before 1800 hours. On the Davis County area, 22 percent occur before 0600 hours, 45 percent before 1200 hours, and 72 percent before 1800 hours. In general, the pattern of storm occurrence in the Great Basin area conforms to the popular concept that most of the storms occur between 1000 and 1800 hours, peaking at about 1300 hours. However, the pattern in the Davis County area does not; it is more nearly uniform. There is a slight but steady increase in storm occurrence up until 2000 hours followed by a sharp decrease up until midnight. These differences in storm occurrence are probably associated with the principal source of summer moisture and atmospheric instability mechanisms. In the Great Basin area, thermal convection is the principal source of thunderstorms and the Gulf of Mexico is the chief source of moisture. In the Davis County area, two

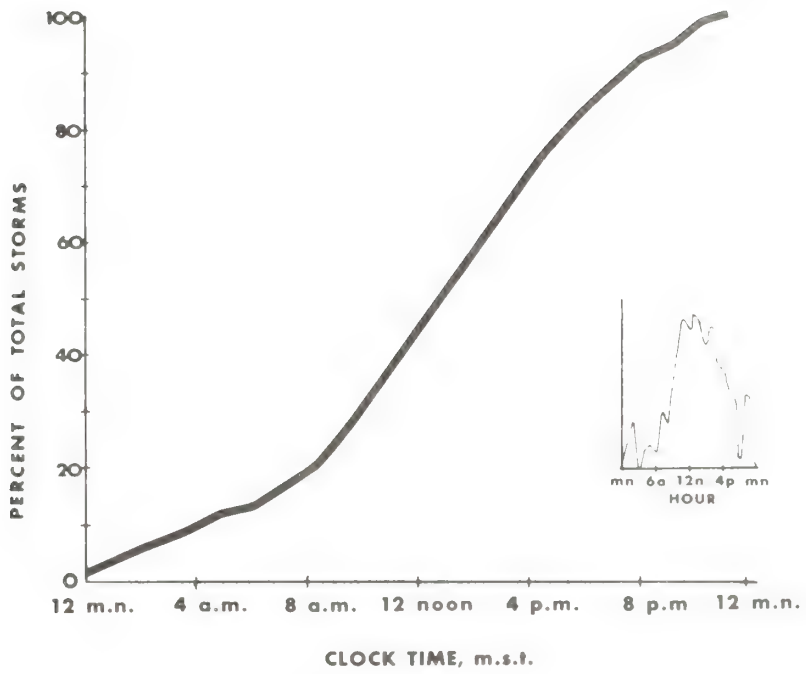

Figure 5.--Mass curve of accumulated percent of total storms by hour of storm beginning, for precipitation Zone 3 of the Great Basin Experimental Area. The inset is a schematic showing the distribution of storms by hour.

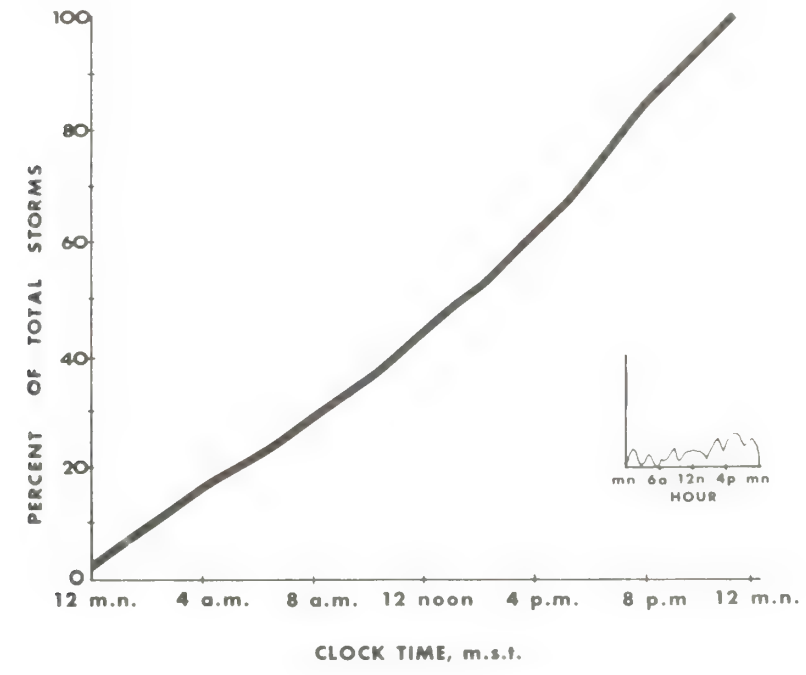

Figure 6.--Mass curve of accumulated percent of total storms by hour of storm beginning, for precipitation Zone 3 of the Davis County Experimental Watershed. The inset is a schematic showing the distribution of storms by hour.

sources of moisture probably exist--the summer-circulation pattern that pulls moisture northward from the Gulf of Mexico and the weak cold fronts that move inland from the Pacific Ocean. These weak fronts are often of the underrunning type and trigger frontal showers and thunderstorms. The arrival of these cold fronts is independent of time. Therefore, the curve for the Davis County area does not peak markedly in the early afternoon. However, thermal convection is a common occurrence here, and this mechanism increases the occurrence of afternoon and evening thunderstorms. Weak summer cold fronts often pass to the north of the Great Basin area.

Storm Occurrence by Storm Duration

Unlike the storm-occurrence-by-hour data, these data show only minor differences between study areas, but rather marked differences between elevations. Figures 7 and 8 are mass curves of accumulated percent of total storms by storm duration for Zones 1 and 4 of the Davis County area, respectively. The curves for each zone of the Davis County area are typical of those for the Great Basin area. Figures 7 and 8 are the two extremes of the Davis County area.

As elevation increases from 4,350 feet in Zone 1 to 8,760 feet in Zone 4, the storms become notably shorter. Thus, in Zone 1, 25 percent of the storms last less than 70 minutes, 50 percent less than 135 minutes, and 75 percent less than 255 minutes. Thirteen percent of the storms exceed 6 hours in length. In Zone 4, 25 percent last less than 55 minutes, 50 percent less than 100 minutes, and 75 percent less than 155 minutes. Only 4 percent exceed 6 hours in length.

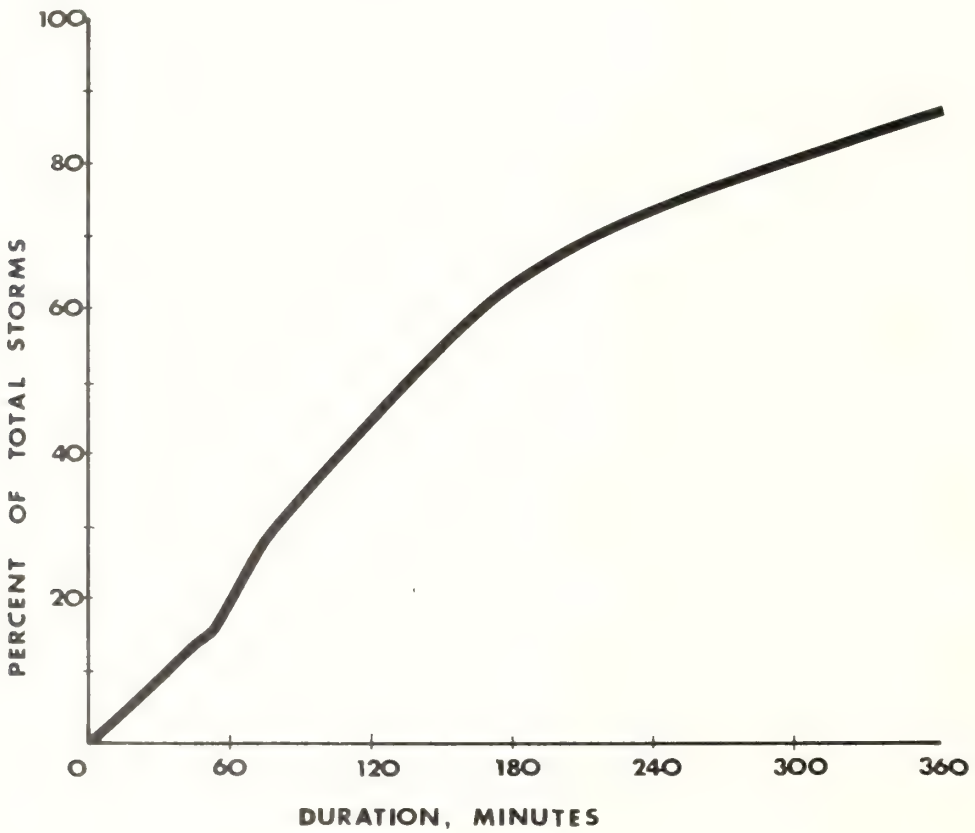

Figure 7.--Mass curve of accumulated percent of total storms by storm duration for precipitation Zone 1 of the Davis County Experimental Watershed.

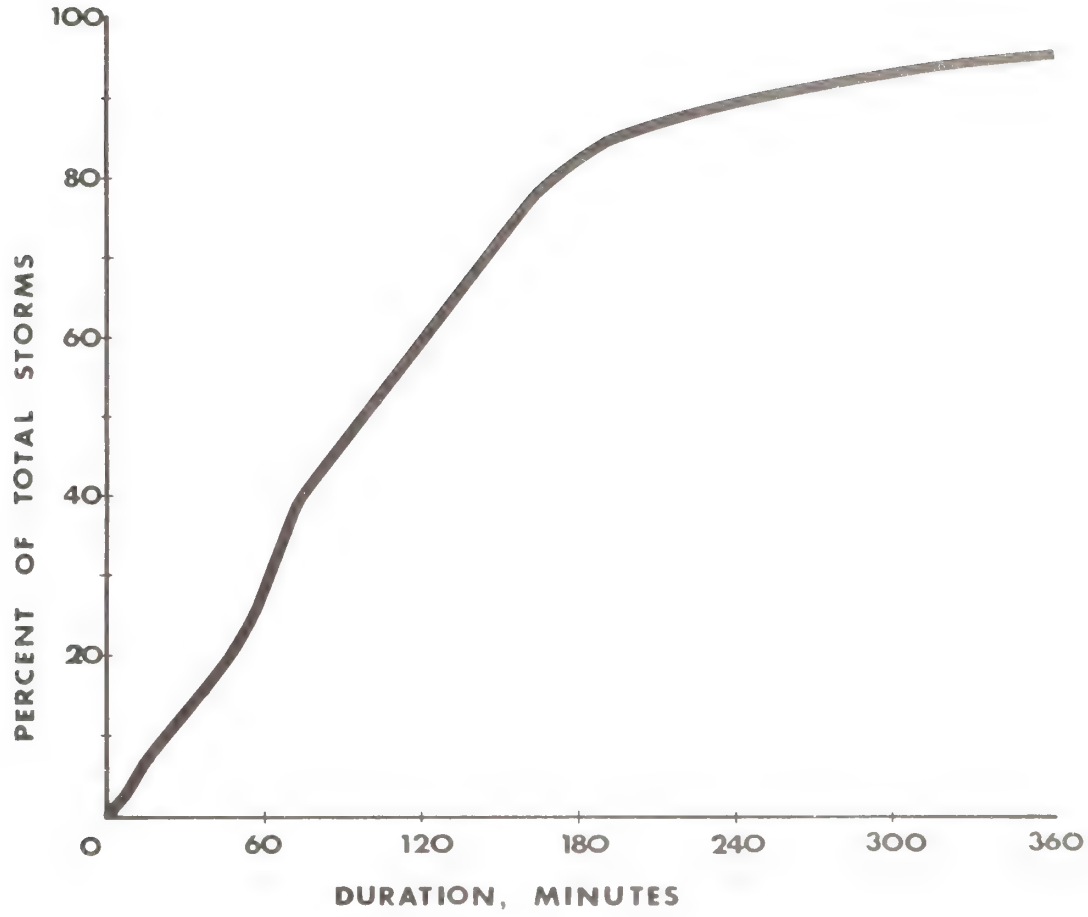

Figure 8.--Mass curve of accumulated percent of total storms by storm duration for precipitation Zone 4 of the Davis County Experimental Watershed.

DISCUSSION

In general, the mountain-valley intensity relationships stated by Brancato (1942) hold true for these data. He stated:

> With regard to variation of thunderstorm rainfall with elevation...over a long period of time a station located at a lower elevation is likely to experience the most intense thunderstorm.

Dorroh (1946) also substantiates this hypothesis. However, the maximum expected rainfall intensities in the aspen-fir type are somewhat lower than those expected at either higher or lower elevations.

Plant cover destruction resulting in active flood and sediment source areas has occurred prevalently on high-elevation herbaceous sites that lie above the aspen-fir type, and was due primarily to summer grazing overuse by livestock. Our data show that the rainfall intensities expected to occur on such sites are quite substantial.

Some of the rainfall intensities that can be expected to occur probably will be greater than the infiltration capacities of some sites, particularly those in poor hydrologic condition. Hence, overland flow is almost a certainty. Fortunately, management practices on mountain watersheds can drastically alter runoff volumes and flood peaks. This has been amply and convincingly demonstrated on the Davis County Experimental Watershed (Bailey et al. 1934 and Bailey et al. 1947). On both study areas in the middle 1930's, severe mud-rock floods were generated by storm events with a recurrence interval of only 15 years. Since that time, both vegetal and mechanical rehabilitation measures have resulted in the satisfactory disposition of storm rains of equal or greater magnitude.

Fortunately, the greatest annual rainfall intensities can be expected to fall on the oakbrush type. Historically, flood source areas have not existed in this vegetal type. However, vegetal conversion as a means of increasing water yields from the oakbrush type has been considered. The potential hydrometeorological implications of such conversions are clear--the resulting vegetal type should be able to handle storm rainfall of high intensity without producing serious flood concentrations or soil erosion. Regardless, urban encroachment and the paving of areas within the oakbrush type can be expected to produce localized flooding.

Depth-duration curves suggest that the longer the storm, the greater the runoff. Osborn (1964) has pointed out that the use of depth-duration data can result in misleading runoff values. He reported that, in the semiarid southwest rangeland, major runoff events are often the result of short-lived, high-intensity convective storms. Osborn's conclusion is generally applicable to our study areas. Major amounts of summer runoff will usually come from storms of medium duration, i.e., 2 to 6 hours, with short periods of high-intensity rainfall bursts.

Apparently, no firm relationship exists between summer precipitation on the lowest and on the highest zones. Clyde (1931) was unable to establish a relationship between precipitation in the valleys with that in the mountains. The long term averages of monthly depth show that the ratio between highest and lowest zones varies between 1.2 and 4.1. But in any given year, these ratios may be quite different. Nonetheless, there is a definite trend toward greater average monthly depths with increasing elevation. There are no indications that precipitation depth decreases above a certain altitude.

Although the mountain-valley intensity relationships tended to follow Brancato's (1942) thesis that the lower lying stations receive the most intense rainfall, our data do not support his contention concerning the amount of rainfall. He stated:

> Three to four times as many thunderstorms occurred on the middle and upper windward slopes of the mountains as on the relatively flat and lower portions of the basin. However, contrary to published and popular accounts, the thunderstorms produced the greatest amount of precipitation at the lower elevations and not on the mountain slopes. The most favorable condition for the production of heavy rain is the presence of an air mass with a sufficient amount of available energy and the greatest possible amount of moisture. Orographic lifting is very effective as a mechanism to release the latent energy in an air mass, but as the air is lifted over progressively higher terrain, the total amount of available precipitable water above any given area becomes progressively smaller.

Two assumptions upon which Brancato bases his thesis might be questioned. One is the assumption that the amount of precipitable water in an airmass becomes significantly less as it is forced over a single mountain crest. It is not likely that the total precipitable water changes very much on adjacent precipitation zones. Significant diminution of precipitable water requires the passage of an airmass over substantial sections of terrain. Another is the assumption that orographic lifting is the dominant mechanism triggering storms. Orographic effects may well contribute to summer shower activity, but the local daytime slope heating and induced upslope breezes are probably more important. Cold fronts and upper troughs may also contribute to some of the storms, especially early and late in the season. These may act in conjunction with daytime surface heating and orographic lifting.

The relation between elevation and number of storms is similar to that between elevation and average monthly rainfall depth. The ratio between the number of storm occurrences at the highest zones and at the lowest zones varies between 0.7 and 1.6.

Table 5.--*The ranges of 60-minute rainfall intensities, in inches per hour, for the 10- and 50-year recurrence intervals by regions*

Region	10 years	50 years
Central & southern Idaho	0.22-0.45	0.38-0.77
Northern Utah	0.37-0.86	0.96-2.20
Central Utah	0.62-0.86	0.98-1.20
Southern Utah & northern Arizona	1.11-1.50	1.69-2.00
Southern Arizona	1.61-1.99	2.22-2.60

What is the areal applicability of the intensity data? In addition to the information presented here, data are available for 41 additional intensity gages located in New Mexico, Arizona, Utah, and Idaho. The additional data include intensity-frequency information for the 60-minute durations (table 5).

The trend toward greater intensities is inescapable if one examines the hourly data at the most northern gages, which are in central Idaho, and then progressively moves to the more southerly stations in southeastern Idaho; northern, central, and southern Utah; and northern and southern Arizona. Some anomalies are present, but this is expected since these stations are grouped irrespectively of elevation, physiography, and source of summer moisture. For any given recurrence interval, our data (figs. 3,4) probably underestimate the 60-minute rainfall intensities for stations in southern Utah and Arizona and overestimate those for southern and central Idaho. This relationship is expected to hold for all durations from about 30 minutes to 24 hours.

Evidence that rainfall intensities in all of these areas may be reasonably comparable for durations shorter than 30 minutes exists in maximum observed 2-minute intensities for selected stations in Idaho, Utah, and Arizona as follow: Reynolds Creek, Idaho, 17.08 inches per hour; Oaks Climatic Station, Utah, 14.40 inches per hour; and Tombstone, Arizona, 18.21 inches per hour. The maximum differences in these intensities only amount to 0.13-inch depth in 2 minutes.

Kidd (1964), working in south-central Idaho, reported the 15-minute, 4-year return period intensity as 3 inches per hour. His period of record was only 5 years. This is about an inch per hour greater than would be expected in northern and central Utah.

Keppel and Fletcher (1958) reported the 20-minute, 100-year rainfall intensity as 6 inches per hour in southern Arizona. This is very close to the extrapolated 100-year value of 5.8 inches per hour for precipitation Zone 1 on the Davis County Experimental Watershed. They also reported that 80 percent of the storms lasted less than 4 hours. This compares quite favorably with our findings.

The transposition of these data to other areas should be approached cautiously. However, for low-risk hydrologic design problems, the data for durations less than 30 minutes are probably representative of many windward mountain slopes throughout southern Idaho, eastern Nevada, Utah, and Arizona. At durations of 30 minutes and greater, rainfall intensities reported here are probably too high for the northern part of this region and too low for the southern part.

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FARMER EUGENE E. and FLETCHER JOEL E.

1971. Precipitation characteristics of summer storms at high-elevation stations in Utah. USDA Forest Serv. Res. Pap. INT-110, 24 p., illus.

This paper presents results of precipitation data analyses for two mountain networks of precipitation intensity gages. All data were collected during the period May 1 to October 31.

Analyses included: (1) Delineation of local precipitation zones, (2) intensity-duration-frequency characteristics, (3) 24-hour depths, (4) monthly depths and number of storms, (5) storm occurrence by hour of the day, and (6) storm occurrence by storm duration.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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INFILTRATION AND WATER REPELLENCY IN GRANITIC SOILS

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INFILTRATION AND WATER REPELLENCY IN GRANITIC SOILS

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ABSTRACT

Water repellency in the granitic soils of the Carson Range of the Sierra Nevada can be a major limiting factor in the capacity of these soils to absorb high-intensity summer rainfall. Results of infiltrometer tests indicate that water repellency often impedes infiltration beneath pine litter, but rarely does so under chaparral cover. Water repellency tends to develop in a continuous layer at the soil surface under pine litter. Fortunately, this layer is usually disrupted by growing roots, burrowing rodents, and other biologic activity; so water can penetrate at a few points and spread into the wettable subsoil. Patches of water-repellent soil were often found under chaparral, but no tendency for the development of a continuous layer was detected.

INTRODUCTION

Affinity for water is one of several soil properties that determine infiltration rates. In some soils, particularly sandy soils, there are zones that have little affinity for water and that, in fact, repel water because surfaces of the minerals in such zones are coated with hydrophobic organic substances. The extent to which water repellency affects infiltration depends not only on its severity, but also on its distribution within the soil mantle. If repellency is mild or is limited to a few scattered patches, its effect on infiltration is minor. At the other extreme, no infiltration is possible if the entire soil surface is severely repellent.

The mechanisms involved in the formation of water-repellent soils are not well understood, partly because the hydrophobic compounds have not been identified. These compounds are formed and released from plants and plant residues by decomposition and pyrolysis. They may be formed in the soil by fungi and other microflora (Bond and Harris 1964) or they may move into the soil after formation elsewhere.

It is known that hydrophobic compounds are released by combustion of litter and move as vapors into the soil (DeBano 1966). Similarly, the high temperatures induced by fire pyrolyze soil organic matter and vaporize hydrophobic compounds already present in the surface soil. A portion of these vapors escape to the atmosphere, but some diffuse downward in the soil to condense on cooler mineral surfaces (DeBano and Krammes 1966). This action results in a soil profile that has a wettable surface but a layer of water-repellent soil exists an inch or so below the soil surface. Infiltration into such a soil may cease entirely when the wettable surface layer becomes saturated.

The following hypothesis is offered to explain water repellency that has not formed in place and has not been caused by fire. Decomposition of plant litter may release compounds that are carried by water into the soil where they are absorbed on mineral surfaces and become hydrophobic as the soil dries. This process is probably slow; several years may be required for formation of severe repellency. Its existence may be difficult to prove.

Sandy soils are more susceptible to water repellency than finer-textured soils. Virtually all reported cases of water repellency involve soils of the coarser textures. Severity of water repellency appears to be inversely related to area of mineral surface per unit weight of soil. Clay apparently moderates or dilutes hydrophobic substances in the soil; clay particles have much more surface area per unit weight than sand particles and absorb relatively large amounts of the hydrophobic material without becoming sufficiently coated to be water repellent. It is possible, also, that organic substances that are hydrophobic when absorbed on sand particles may be hydrophilic when absorbed on clay particles.

We are only beginning to learn about the nature, geographic distribution, and consequences of water repellency in forest and range watershed soils; little of this research was carried out before 1960.

The possibility of water repellency being an important factor in flood production in the eastside Sierra Nevada was not recognized until 1966 during an infiltrometer study (Hussain and others 1969) in the Jeffrey pine *(Pinus jeffreyi)* type. During that study, infiltration into soil that had a chaparral cover was good, but some plots dominated by Jeffrey pine litter had infiltration characteristics that were surprisingly poor. Water-repellent soils were found in these plots and were held responsible for poor infiltration.

In 1968, Bashir (1969) made a reconnaissance to determine the occurrence of water repellency in the Tahoe-Truckee Basin. Using the water-drop technique (Krammes and DeBano 1965), he found widespread water repellency, varying from a surface phenomenon to an average depth of 5 cm., under all cover types except bare soil.

In 1970, we began a study of the hydrologic characteristics of granitic and andesitic soils in the Carson Range. An investigation of water repellency in these soils is an important part of this research. First-year results pertaining to infiltration and water repellency are reported in this paper.

METHODS

This report is based on observations made on 92 plots on granitic soils at elevations between 5,500 and 9,500 feet in the Carson Range east and northeast of Lake Tahoe. Most of the study sites were in the Jeffrey pine type, and ranged from fully stocked stands of small sawtimber to open brushfields no longer supporting timber. The remainder were in an open lodgepole *(P. contorta)* and western white pine *(P. monticola)* stand on the west face of Slide Mountain.

Infiltrometer

Preliminary investigations revealed that water repellency was usually most severe at the soil surface and that any disturbance of the surface soil (e.g., that caused by driving a plot frame or infiltrometer ring into the soil) could rupture the repellent layer and allow water to bypass it.

To minimize errors due to soil disturbance, we developed a special infiltrometer. (See appendix for construction details.) This infiltrometer consists of a rainfall simulator, similar to the raindrop-producing unit developed by Chow and Harbaugh (1965), and a runoff-collecting trough. The rainfall simulator applies water uniformly to a fixed area (3.7 square feet) at a controlled rate. No plot frame is used; the boundaries of the plot are determined by the area of water application. Plot runoff is caught by a trough at the downhill edge of the area of application. This runoff collector is installed slightly below the soil surface and (when necessary) sealed with caulking compound.

The advantages of this infiltrometer (minimum soil disturbance, ease of operation, and portability) were achieved at the expense of increased probability of errors caused by low raindrop impact velocity and lateral movement of water in the soil. Raindrop impact velocities are much less than those of natural rain because the rainfall simulator is placed close to the soil surface to avoid wind effects and splash off the plot. This is probably unimportant on litter-covered plots where raindrop impact is broken by litter and, if present, by vegetation. However, if the soil surface is bare, infiltration capacity may be overestimated because the low-velocity simulated raindrops do not puddle the surface soil as much as high-velocity natural raindrops would. The absence of a plot frame increases the opportunity for lateral movement of water after it enters the soil. Serious errors due to lateral movement were found in this study only where a subsurface water-repellent layer existed under readily-wettable surface soil. These errors do not constitute a problem if they are recognized and taken into consideration when interpreting results.

Field Procedures

The rainfall simulator and the runoff trough were installed with the least possible disturbance to vegetation, litter, and soil. When present, erect shrubs had to be removed from a plot to allow proper installation and operation of the rainfall simulator. Pruning shears were used to avoid disturbing the litter or soil. Shrub removal had little effect on infiltration characteristics other than eliminating the water storage capacity of the canopy.

Water was applied to each plot at a constant rate of 12.0 cm./hr. (4.72 inches/hr.) for 30 minutes. All plot runoff was collected and measured at 3-minute intervals. After the infiltration test, all litter was removed from the plot and weighed. This litter was air dried to determine approximately how much of the applied water was retained by the litter. Three soil samples were taken in the surface 6 cm. of soil with a San Dimas core sampler for determination of hydraulic conductivity, bulk density, porosity, texture, and organic matter content.

The lower half of the plot was dug out to determine the location and shape of the wet front, lateral movement of water from the sides and bottom of the plot, and the locations and shapes of water-repellent zones. Samples were taken in the wetted soil on the plot and in unwetted soil at the same depths adjacent to the plot. These were ovendried to determine antecedent moisture content and moisture content of the wetted zone. These data, in combination with bulk density and average depth of wet front, permitted an approximation of how much of the applied water entered the soil.

RESULTS AND DISCUSSION

All granitic soils sampled in this study fell within the sand and loamy sand textural classes. Sand content of the surface soil of the plots ranged from 80 to 95 percent and averaged 89 percent. Clay content ranged from 2.4 to 4.5 percent and averaged 3.5 percent. With few exceptions soil bulk density was less than 1.6 g./cc.; and generally less than 1.4 g./cc. The infiltration capacity of such coarse, porous soils is excellent in the absence of water repellency. However, water repellency was encountered on most of the plots, varying in degree from a barely perceptible slowing of the wet front to a virtually complete halting of the wet front. Where a high degree of water repellency was present, its distribution in the soil profile ranged from a few isolated patches to a thick, continuous layer.

Wetting Patterns

The wetting pattern in the soil of each plot was exposed by digging a trench across the middle of the plot after water had been applied for 30 minutes. Although no two wetting patterns were exactly alike, they could be classified into eight general types, depending on size, continuity, and location of water-repellent zones (fig. 1).

Pattern 1 is the typical wetting pattern of homogeneous, wettable soils. This pattern was found only in openings devoid of vegetation and litter.

Pattern 2 occurred where the soil surface was covered by litter. Live plants were usually present. The wet front is irregular because the soil is not homogeneous. The irregularity is due primarily to variations in soil porosity, but it is believed that variations in soil wettability are partially responsible in some cases.

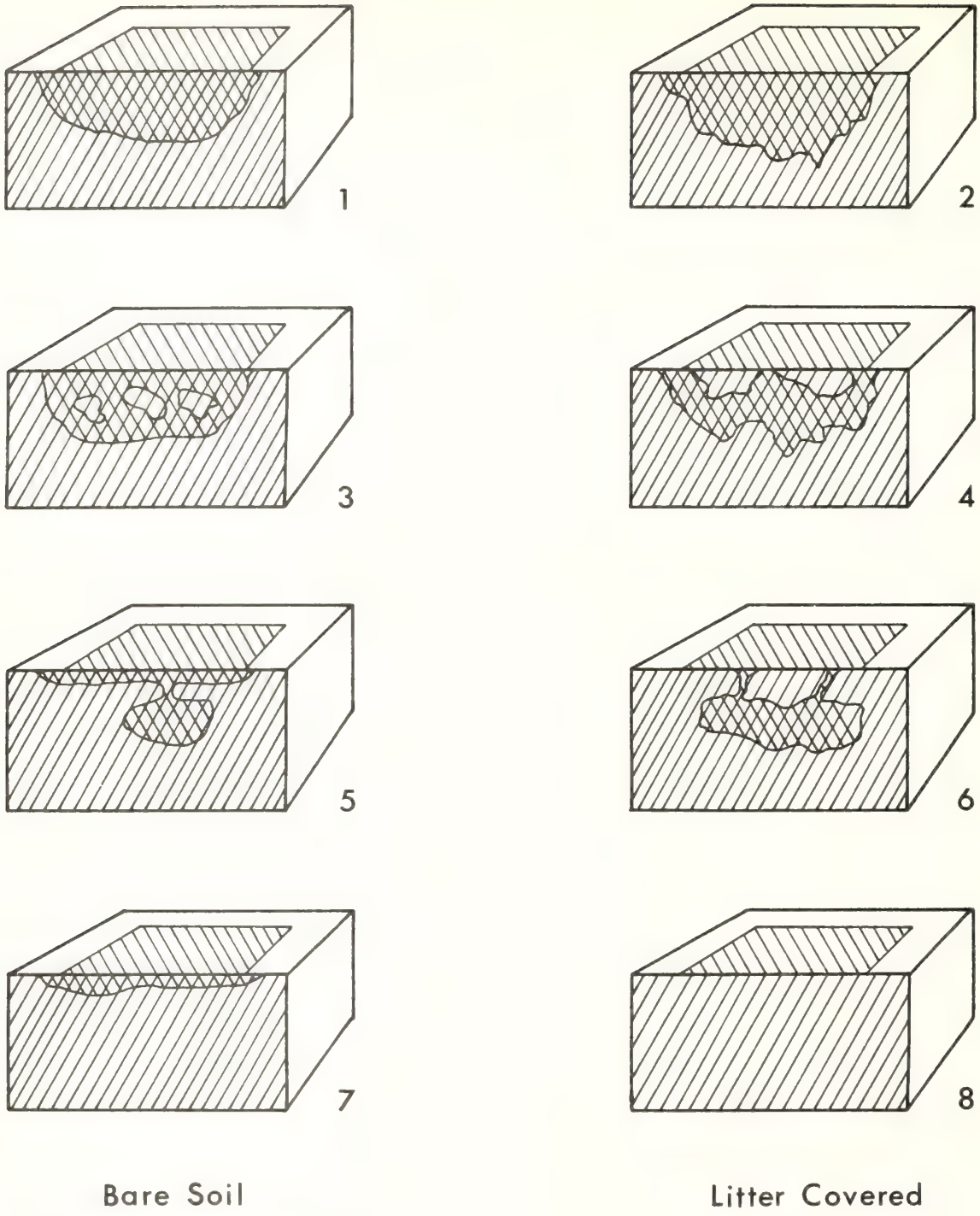

Figure 1.--Eight generalized wetting patterns.

In Pattern 3, there were isolated patches of dry soil within the wetted zone but not at the soil surface. The dry patches occasionally surrounded roots from nearby shrubs or trees, but not all roots were surrounded by dry soil, nor were the dry patches confined to the vicinity of roots. This pattern usually, but not invariably, occurred in bare openings. Little or no runoff was produced by plots having Patterns 1, 2, or 3.

In Pattern 4, portions of the surface soil remained dry and were bypassed by the wet front. Litter was always present over the dry patches. When live vegetation was present, it was usually growing on the wetted portions of the soil surface. Dry patches varied widely in area and thickness, and the amount of runoff produced varied accordingly.

In Pattern 5, there was a discontinuous water-repellent layer 1 to 3 inches below the bare soil surface. The surface soil was readily-wettable and breaks in the water-repellent layer allowed the wet front to penetrate the wettable soil below the layer. Runoff from plots with this pattern was severe unless there were many breaks in the water-repellent layer.

Pattern 6 was found on litter-covered plots where the discontinuous water-repellent layer was at the soil surface. This pattern was rarely found when there were live shrubs on the plot. Runoff from plots with this pattern varied widely but tended to be less than that of plots with Pattern 5 because there were usually more breaks in the water-repellent layers formed under litter.

Pattern 7 was found in bare plots where there was a continuous water-repellent layer 1 to 3 inches below the soil surface. Runoff was severe because the surface layer of soil provided the only available storage for water.

Pattern 8 is the extreme case where there were no breaks in a water-repellent layer at the surface. This pattern was found under pine litter only on plots that had no understory. Pattern 8 produced more runoff than any other because the only available water storage was in the litter that--being somewhat water repellent also--held very little water.

Infiltration Curves

There was little or no runoff from the plots with wetting patterns 1, 2, or 3. Many of these plots appeared to have infiltration capacities well in excess of 4.7 inches/hr., the application rate. Runoff from plots with Pattern 4 was generally slight because the wettable portions of the soil surface absorbed the runoff from the water-repellent portions. However, if more than about two-thirds of the soil surface remained dry during the 30-minute application of water, runoff was great enough to indicate that infiltration capacity was less than the rate of application. All plots with wetting Patterns 5 through 8 produced appreciable runoff.

Typical infiltration curves are shown in figures 2 and 3. These curves are based on actual measurement of runoff during the 30-minute application. Curve 4 is the average of two plots with wetting Pattern 4 on which more than two-thirds of the soil surface remained dry during the 30-minute test. The gradual increase during the latter part of the test is typical of plots with incomplete water repellency. In fact, runoff began at about 3 minutes and ceased after about 15 minutes on four plots in this category. This phenomenon is believed to be caused by mild water repellency in the wettable portions of the soil surface. Once the wet front penetrates the slowly-wettable portions of the soil surface and enters the more absorbent soil below, its rate of advance increases.

Curve 6A is the average of infiltration rates on three plots that had wetting Pattern 6 and many breaks in the water-repellent layer. Curve 6B is based on four plots that had few breaks. The curves are basically similar, but infiltration is greater in plots that water penetrated at more points.

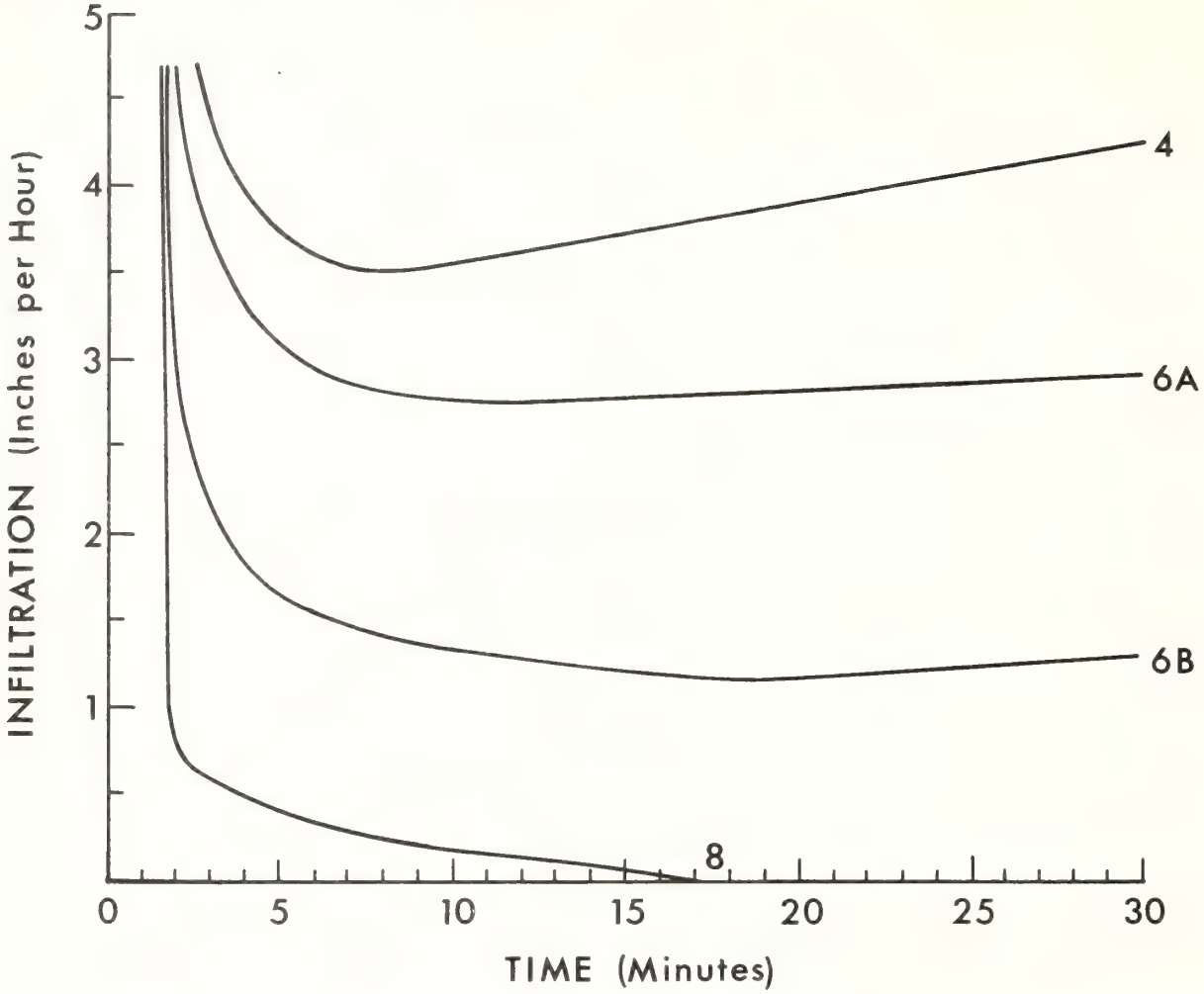

Figure 2.--Infiltration into litter-covered water-repellent soils.

Curve 8 was obtained on a plot that had severe water repellency at the soil surface (Pattern 8). All water applied ran off, except for that absorbed by the somewhat water-repellent litter. Since all soil remained dry, there was no opportunity for lateral flow. In a strict sense, no infiltration occurred.

Curve 5A in figure 3 is the average of infiltration on bare plots that had wetting Pattern 5 and many breaks in the water-repellent layer. The initially high infiltration is due to the absorbent surface soil. Infiltration decreases when the wet front reaches the water-repellent layer and then increases again as water penetrates the breaks in that layer and spreads out into the wettable soil below. Curve 5B is based on a plot that also had a subsurface water-repellent layer, but fewer breaks and, consequently, more runoff than the ones of curve 5A.

MEEUWIG, RICHARD O.

1971. Infiltration and water repellency in granitic soils, USDA Forest Serv. Res. Pap. INT-111, 20 p., illus.

The granitic soils of the Carson Range of the Sierra Nevada are often water repellent to some degree. Under chaparral cover, water repellency tends to be patchy and rarely impedes infiltration appreciably. Under coniferous litter, it tends to form a continuous layer in the surface soil and, on some sites, can curtail infiltration and cause accelerated runoff.

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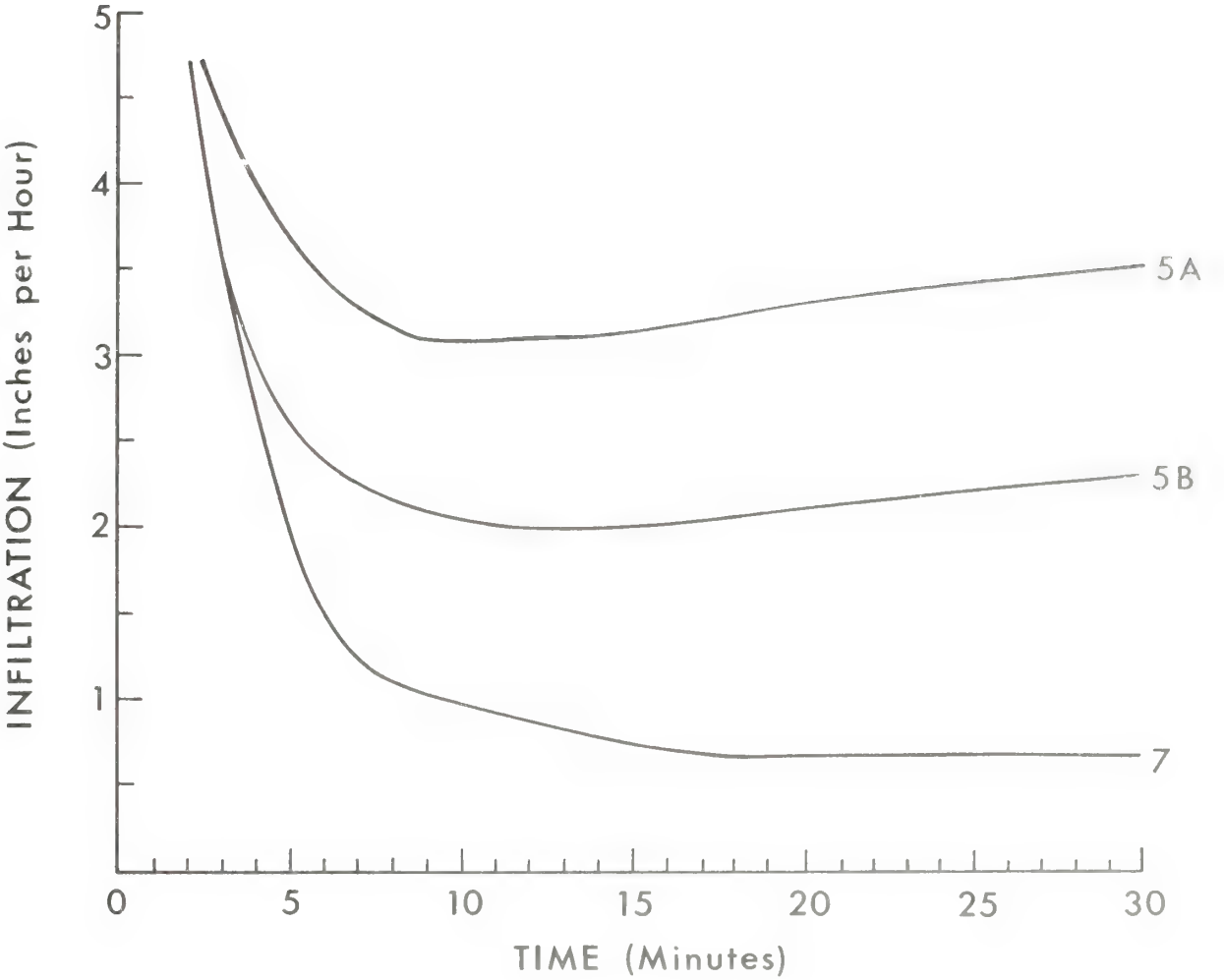

Figure 3.--Infiltration into bare water-repellent soils.

Curve 7 is from a plot having a continuous subsurface water-repellent layer (Pattern 7). The initially high infiltration is due to the absorbent surface soil. Once the soil above the water-repellent layer was thoroughly wetted, infiltration did not cease entirely--as might be expected--because of lateral flow in the surface soil, but also because of slow penetration into the repellent layer.

Ground Cover Effects

The selection of the number of plots on each ground cover type was based on frequency of occurrence of the cover types, and on variations in infiltration within the cover type. Cover types that had the most widely varying infiltration rates were sampled more intensively. The number of plots is too small to allow valid statistical tests

Table 1.--*Average and range of plot runoff, by cover types, generated by the uniform application of 2.36 inches of water during a 30-minute period.*

Cover type	Number of plots	Inches of runoff	
		Mean	Range
Jeffrey pine litter	30	0.84	0.00-1.81
Western white pine litter	6	1.83	1.31-2.23
Greenleaf manzanita	13	0.10	0.00-0.27
Squaw carpet	5	0.13	0.00-0.31
Bitterbrush	5	0.26	0.00-0.75
Pinemat manzanita	3	0.35	0.00-0.56
Tobaccobrush	8	0.38	0.00-0.75
Bare	22	0.36	0.00-1.71

of differences between cover types. But, the results are of value and interest even though no statistically defensible conclusion can be drawn. The numbers of plots dominated by each species are listed in table 1 along with their average runoff and range of runoff values. The criterion for dominance usually was based on the species that was most prevalent in the litter on a plot. Exceptions were made when live vegetation appeared to override the influences of the litter.

Jeffrey pine.--After a 30-minute wetting, dry surface soil, varying from a single small patch to a nearly continuous layer, was found on 28 of the 30 plots dominated by Jeffrey pine litter. Of the two plots that had wetting Pattern 2, one produced no runoff. The other yielded 0.1 inch of runoff, probably because of water-repellent litter. The remaining 20 plots were about equally divided between wetting Patterns 4 and 6, and produced from 0.2 to 1.8 inches of runoff. Litter cover on these plots varied from a thin layer, covering about two-thirds of the plot, to a complete cover 4 inches thick. Where litter cover was incomplete, there was a tendency for the patches of bare soil to be absorbent; such plots produced little runoff. Where litter cover was complete, no relation between litter depth and runoff was detected. There was a definite correlation between litter depth and thickness of the water-repellent layer but this was offset by a tendency for more and larger breaks to occur in the water-repellent layer beneath thick litter, probably because of greater soil fauna activity.

Western white pine.--The six plots in this group were situated at an elevation of about 9,300 feet on the west face of Slide Mountain. All six had a thin but essentially complete cover of pine needles, mostly western white pine but some lodgepole pine. Soils beneath this litter were the most repellent found in this study. The thickness of the severely water-repellent layer ranged from 3 to 6 inches, and moderate repellency was found to extend as deep as 18 inches. While it is possible that western white pine and lodgepole pine are more conducive to the formation of water-repellent soils than Jeffrey pine, extreme repellency at this site may be attributable to the limitations imposed by a harsh microclimate on soil biota. There was much less evidence of faunal activity in these soils than those at lower elevations. The scarcity of understory vegetation aggravates this situation.

The plot that absorbed the most water (1.05 inches) had a small clump of bunchgrass *(Stipa* sp.*)* under which the soil was wettable enough to allow penetration of the wet front. Pinemat manzanita *(Arctostaphylos nevadensis)* was growing on another plot and water was able to penetrate along some of its roots but this plot absorbed only 0.75 inch of applied water.

The other four plots were devoid of live vegetation. Three of these plots absorbed 0.30 to 0.55 inch of water because water penetrated the water-repellent layer at one or two points. There was no soil wetting whatsoever on one plot, and only 0.13 inch of water was absorbed by its litter.

Shrubs.--Average runoff from the shrub plots was much lower that that from pine plots because soils on such sites were less repellent. Although patches of dry surface soil (Pattern 4) were found on most of the shrub plots after the water application test, they were never extensive enough to cause runoff in excess of 0.75 inch.

Most shrub plots were close to pine trees and had varying amounts of pine needles on them. The litter on squaw carpet *(Ceanothus prostratus)*, pinemat manzanita, and bitterbrush *(Purshia tridentata)* plots usually contained more pine needles than shrub leaves; apparently these species produce relatively little litter, but efficiently trap pine needles. Tobaccobrush *(C. velutinus)* and greenleaf manzanita *(A. patula)* are more prolific litter producers, and pine needles were usually a minor constituent of litter on plots dominated by these species. Because of the admixture of pine needles, it is uncertain how much of the water repellency was derived from shrub species. However, the results suggest that shrubs rarely cause serious water repellency; on the contrary, they increase infiltration into soil rendered water repellent by pine residues. The prostrate shrubs, squaw carpet and pinemat manzanita, seem to be especially effective in disrupting water repellency because their roots penetrate the surface soil at many points.

Of the five shrub species tested, tobaccobrush produced the highest average runoff and probably had the most water-repellent soil. Greenleaf manzanita had the lowest average runoff and the least repellent soil. Since the amounts of pine litter were approximately equal on plots of both species, it appears that greenleaf manzanita is superior to tobaccobrush with respect to infiltration and soil wettability. Since plots of the other three shrub species generally had more pine litter than tobaccobrush or greenleaf manzanita, no judgment could be made as to their respective potentials to induce water repellency.

Bare ground.--There was at least one bare plot in the vicinity of each litter-covered plot. These 22 plots were devoid of live vegetation. There were pine needles on some of them but usually these had been cast within the past year and rarely covered more than 10 percent of the plot surface. Without exception, the soil surface was highly absorbent if no litter cover was present. However, there were varying amounts of water-repellent soils below the surface of 11 plots.

Runoff from the 11 plots that had no discernible water repellency (wetting Pattern 1) did not exceed 0.16 inch of water, and six of them produced no runoff at all. Seven plots had patches or pockets of dry soil above the wet front (Pattern 3); total infiltration during the 30-minute test varied from 1.65 to 1.89 inches on these plots. Two plots had discontinuous water-repellent layers about 2 inches below the soil surface (Pattern 5) and absorbed 1.18 and 1.52 inches of water. Two plots had continuous water-repellent layers 1 to 2 inches below the soil surface (Pattern 7) and absorbed only 0.65 and 0.80 inch of the applied water.

Soil porosity may have had some effect on infiltration on some bare plots because there was a tendency for them to have higher bulk densities than litter-covered plots, but water repellency was definitely the main factor. All plots with more than 0.16 inch of runoff had extensive subsurface water repellency.

The manner in which water repellency is formed in bare soils is not clear. Pockets of water-repellent soils may be caused by fungal action on live and dead roots of plants adjacent to the bare openings. The subsurface layered water repellency of Patterns 5 and 7 is typical of that found in burned-over areas (DeBano 1969) but there was no clearcut evidence of recent burning on any of the four plots that had these patterns. Two were in a logged Jeffrey pine area that may have burned 10 or more years before. One plot was in an opening within a Jeffrey pine stand that showed no evidence of either burning or logging. The fourth was in a western white pine stand where ground cover was too scattered to support a ground fire. It appears that subsurface layers of water-repellent soil can be formed without fire, but further research is needed to define the mode of formation.

More runoff probably would have been generated on these bare plots under natural conditions. The impact velocity of natural rain would have compacted the soil surface and reduced its permeability. The measured infiltration into bare plots cannot be compared directly with infiltration into litter-covered plots, because the effect of raindrop impact is negligible on the latter.

CONCLUSIONS

Within the geographical area covered by this study (and probably in many similar areas) water repellency is a major limiting factor in the capacity of granitic soils to absorb high-intensity summer rainfall. Other limiting factors are: (1) Inadequate moisture storage capacity due to thin soil, (2) surface sealing caused by raindrop impact on soil surfaces unprotected by litter and vegetative cover, and (3) low porosity due to compaction caused mainly by human activity. Although this report is concerned primarily with water repellency, it is not meant to imply that the other limiting factors listed are unimportant. On the contrary, they cause serious problems on steep, poorly-vegetated slopes and on heavily-used areas. However, water repellency can curtail infiltration into soils that have sufficient depth, porosity, and cover to absorb high-intensity rain as fast as it falls; and it can further reduce infiltration of water into soils where one or more of the other limiting factors are present.

At times, even though no water repellency was found at the surface of bare soil, severe repellency was found below the surface. Some repellency may be residual from past fires, but much of it is believed to be caused by fungal activity on plant roots that frequently occupy the soil under bare openings. If the subsurface repellent layer is continuous and unbroken, infiltration is limited to the storage capacity of the wettable surface layer and severe runoff and erosion will occur during high-intensity storms. The best control in such openings would be obtained by establishing plants in them. Establishment of plants on such sites is difficult, but could be facilitated by destroying the live roots already present under the bare openings.

Water repellency does not appear to be a problem under shrub cover because it is broken up by numerous roots, rodent burrows, and by other means not yet identified.

Water repellency was most severe under pine litter, particularly at higher elevations. If there were no understory or soil fauna activity, it is believed that a continuous water-repellent layer would form under pine litter, rendering the surface soil so impermeable that overland flow would occur even during low-intensity winter rains and spring snowmelt. Fortunately, water repellency that severe is probably limited to a few isolated areas where understory is scarce and activity of soil fauna restricted by climate or food.

The best approach to correct or to prevent excessive water repellency in the soil beneath pine litter would be to encourage the activity and growth of those agents that disrupt the water-repellent layer. Some of these have been identified but there are probably many others yet to be recognized. Understory shrubs and herbaceous plants directly reduce water repellency when their roots penetrate water-repellent layers. They indirectly reduce water repellency by providing food for other organisms that attack water repellency.

Burrows of deer mice *(Peromyscus maniculatus)* were observed to penetrate water-repellent layers, permitting rapid transit of water into absorbent soil below. Other burrowing rodents probably perform the same service. These rodents are considered pests because they consume tree seeds, but, under some circumstances, they should be encouraged because of their benefit to infiltration.

Numerous small and large breaks in water-repellent layers were found that did not appear to have been caused by live roots, old root channels, or rodent burrows. Some of these may have been caused by unidentified arthropods and nematodes. Research is needed to identify and develop means of encouraging the growth of these unknown agents so that water repellency can be controlled by natural means. Such research should include a study of soil bacteria, which may be instrumental in both formation and destruction of hydrophobic substances.

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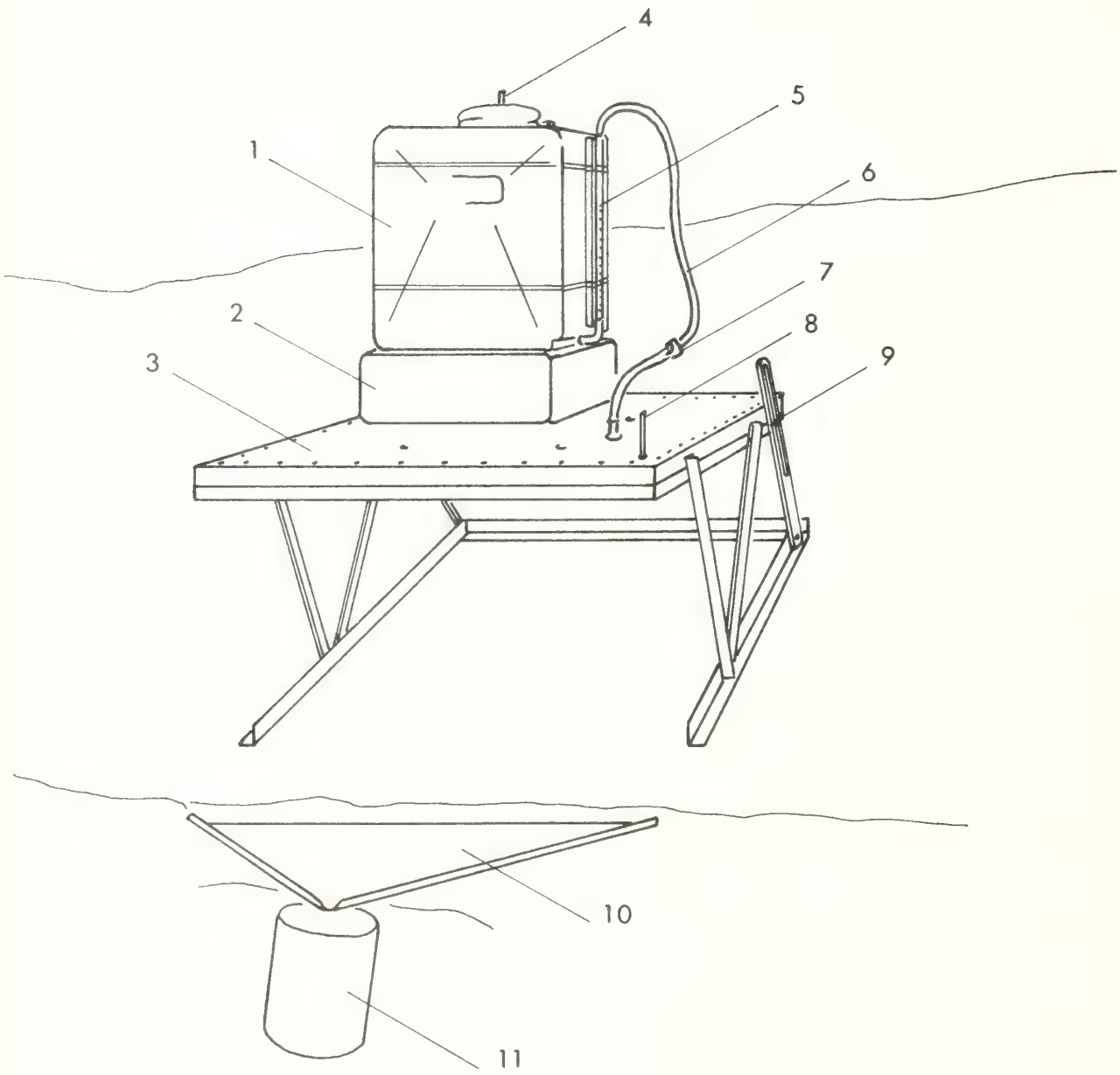

Figure 4.--Infiltrometer.

APPENDIX

Infiltrometer Construction and Operation

In the following discussion, the numbers enclosed by brackets refer to the numbers in figure 4. The water supply [1], a 5-gallon polyethylene bottle with a 1/2-inch tubulature, rests on a 4-inch-high styrofoam block [2] placed on top of the water chamber [3]. A 16-inch-long, 1/8-inch i.d. acrylic tube [4] passes through the bottle cap and allows air to enter at a point about 1 inch above the bottom of the bottle, thus maintaining a relatively constant head. A Manostat (Cat. No. 36-541-30) flow meter [5] is used to measure flow. The 3/8-inch i.d. plastic tubing [6] is connected to the water chamber by a polyethylene quick-disconnect coupler. Flow rate is controlled by an ordinary screw-type tubing clamp [7]. The 6-inch-long 1/8-inch i.d. acrylic tube [8], connected to the water chamber by a polyethylene quick-disconnect, serves three functions: it allows air to escape the water chamber during filling, it indicates water pressure within the chamber, and it facilitates draining.

The water chamber (fig. 5) is similar to the one described by Chow and Harbaugh (1965), but has been modified for field use. It is constructed of plexiglas bolted to angle aluminum. The numbers in parentheses in the figure indicate the number of pieces needed. For added strength, four plexiglas spacers are placed as shown. All joints are sealed with caulking compound. Each dot on the bottom view represents a 3/4-inch-long 23-gage stainless steel tube.[1] These 517 raindrop-producing tubes project 1/8 inch above and 3/8 inch below the lower plexiglas sheet and are held in place with a small amount of epoxy cement. Holes for the tubes were drilled with a No. 71 wire gage drill. Holes for the 5-40 bolts were drilled oversize to 5/32 inch to avoid stress on the plexiglas and to facilitate assembly.

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[1] 0.025-inch o.d., 0.00625-inch wall thickness, obtained from Vita Needle Co., Needham, Mass. 02192.

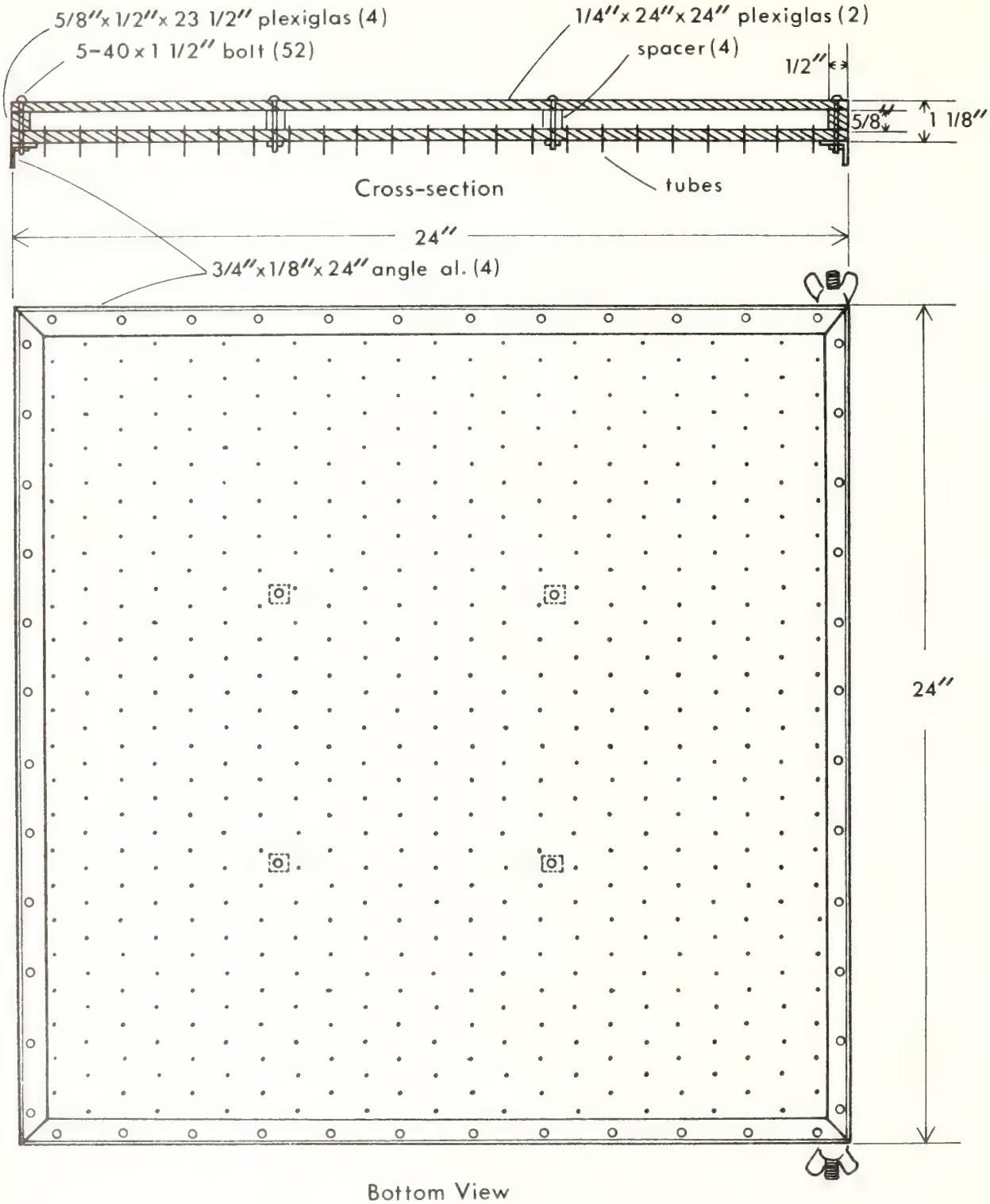

Figure 5.--Water chamber.

The water chamber must be as level as possible. The support frame (fig. 6) is adjustable so that the water chamber can be leveled on slopes up to 60 percent. This could be increased up to about 85 percent by increasing the length of the slots in the slotted bars [9]. The bolts that attach the upright members to the base are secured with locknuts and are left loose enough to allow the limited rotation required for leveling. The collector trough [10] is made from a single piece of sheet steel bent as indicated in figure 6.

The infiltrometer is set up and operated as follows. The water applicator is placed over the area to be tested. A sensitive level is placed on the water chamber and the chamber is leveled along both axes by means of the leveling mechanism [9] and by moving the applicator slightly, if necessary. On steep or slippery slopes the applicator is held in position by stakes driven into the ground inside the upper two corners of the base. After the applicator has been positioned, the runoff collecting trough [10] is installed with its upper edge directly below the lower edge of the applicator. It should be installed slightly below the soil surface, and, if necessary, the uphill edge sealed to the soil surface with caulking compound. A small hole is dug under the outlet of the trough to allow placement of a tin can such as a 2- or 3-pound coffee can [11].

The reservoir is filled and connected to the water chamber. The tubing clamp is opened to allow free flow of water into the water chamber. Few raindrops are produced while the chamber is filling. As soon as the chamber is filled and water moves into the manometer [8], the tubing clamp is quickly adjusted to the desired flow. Rainfall commences as soon as water appears in the manometer and, from then on, its rate responds almost instantaneously to changes in flow-meter readings. It is usually necessary to readjust the tubing clamp from time to time. The reservoir can be refilled during the test if the flow rate is kept reasonably constant by means of the tubing clamp. Runoff into the tin can is measured at desired intervals in a 1,000-ml. graduated cylinder. At the end of the test, water application can be stopped abruptly by kinking the supply tubing and closing the tubing clamp.

Some clogging of the steel tubes can be expected, but can be minimized by using only clean water and by using a screened funnel for filling the reservoir. Distilled water might give better results, but we used tapwater from city supplies and campgrounds and experienced only minor clogging. If a tube clogs, it can be cleaned by pushing a small steel wire up the bore of the tube.

Rainfall intensities from about 1/2 inch per hour to about 10 inches per hour can be obtained with this infiltrometer. The infiltrometer was calibrated at several intensities by operating it on a metal sheet; the results agreed closely with the flow-meter manufacturer's calibration chart.

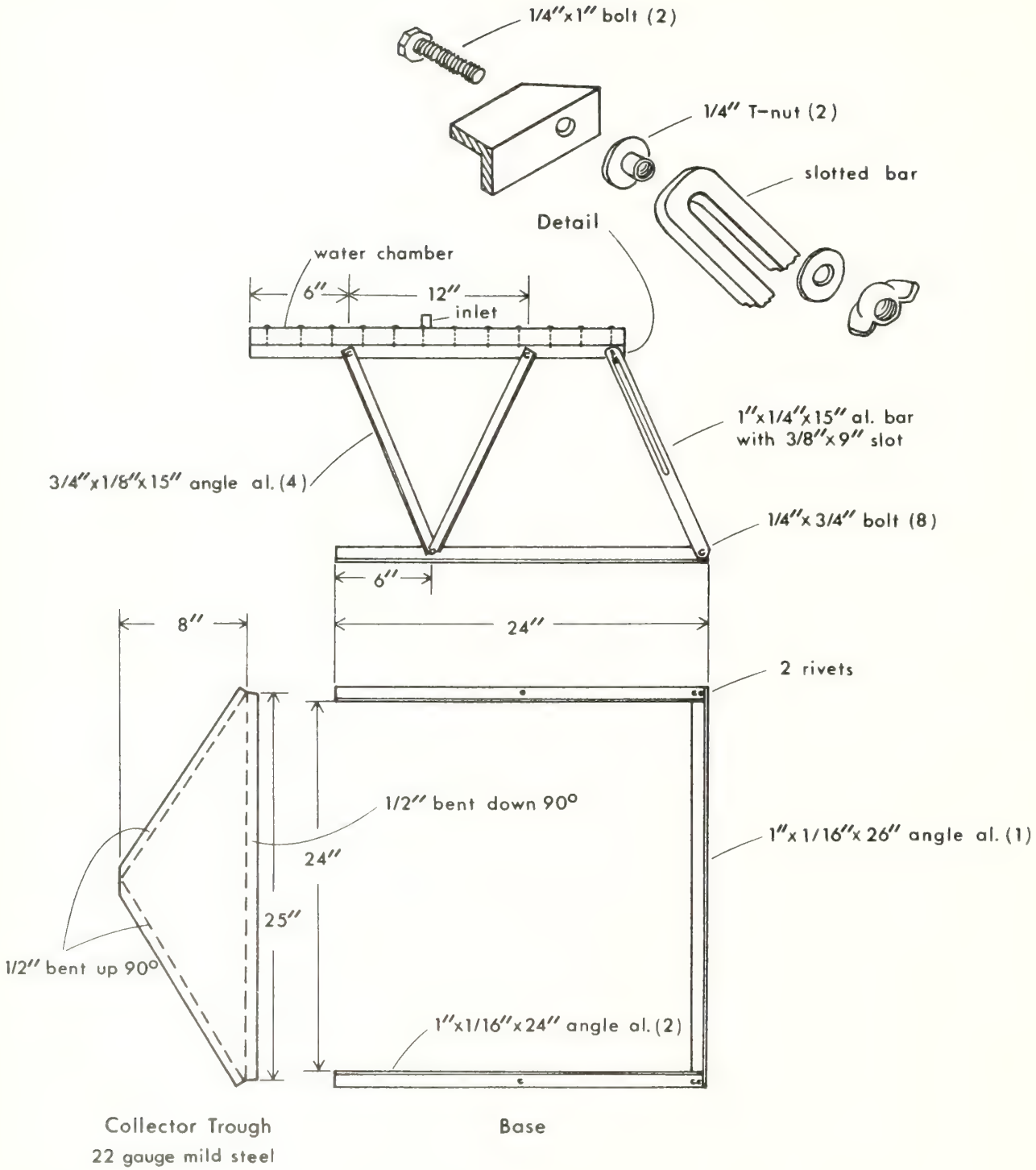

Figure 6.--Support frame and collector trough.

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PONDEROSA PINE SEED— FOR ANIMALS OR TREES?

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(This is a companion report of USDA Forest Service Research Paper INT-86, 1970: "Natural Regeneration in Ponderosa Pine Forests of Western Montana" by Raymond C. Shearer and Wyman C. Schmidt)

ABSTRACT

Ponderosa pine (Pinus ponderosa Laws.) seed development and survival studies in northwestern Montana showed that small forest animals reduced the potential seed crop very little during the 2-year cone development period but they consumed an average of 24 out of 25 pine seeds that matured. Red squirrels (Tamiasciurus hudsonicus richardsoni Bachman) harvested an average of 66% of the mature cones, and after the seeds were dispersed deer mice (Peromyscus maniculatus artemisiae Rhoads), chipmunks (Eutamias amoenus luteiventris Allen), and birds consumed the equivalent of an additional 30%. Deer mouse populations apparently fluctuated in direct response to the size of the previous year's seed crop.

INTRODUCTION

Red squirrels (*Tamiasciurus hudsonicus richardsoni* Bachman), deer mice (*Peromyscus maniculatus artemisiae* Rhoads), chipmunks (*Eutamias amoenus luteiventris* Allen), and birds consume large quantities of pine seeds, particularly in late summer through spring (Curtis 1948, Eastman 1960, and Smith 1943). Conifer seeds provide an important (but not always reliable) source of food for the small mammals and birds. Ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), two common associate species in the Northern Rockies, vary considerably from year to year in their seed crops, producing abundant yields in some years and practically none in others (Roeser 1941, Boe 1954). As a result, animals depending upon these seeds are frequently faced with feast or famine; and populations, particularly of the smaller less mobile mammals, may be affected. For example, deer mouse populations in Douglas-fir forests of Oregon apparently fluctuated in direct response to the previous year's seed crop (Gashwiler 1965). Although the feeding and caching activities of small animals and birds have been observed and reported in some coniferous forests of Oregon (Eastman 1960, Gashwiler 1967), little quantitative data concerning seed use in ponderosa pine forests of the Northern Rockies have been collected. This paper discusses (a) how several factors influence the development and production of ponderosa pine seed, (b) how much seed is used by animals, and (c) how much seed is left to regenerate a new forest.

METHODS

The extent animals and other biological and physical factors influence ponderosa pine seed development was studied during the 33-month period extending from initial ovulate bud formation until seeds are developed, disseminated, and ready to germinate. Stands composed of ponderosa pine and Douglas-fir at Bluesky Creek, Dunn Creek, and Butler Creek east of Libby in northwestern Montana provided the necessary study conditions. Based on the Daubenmires' (1968) ecological habitat system, the areas were classified:

Bluesky----------*Pseudotsuga menziesii/Physocarpus malvaceus*
Dunn----------*Pseudotsuga menziesii/Arctostaphylos uva-ursi*
Butler----------*Pseudotsuga menziesii/Calamagrostis rubescens*

Effects of Animals on Cones

Eight sample trees were selected for study of factors influencing cones during their 2-year development period. These trees averaged 20 inches in diameter at breast height (ranging from 15 to 24 inches); they were randomly selected in a partially cut-over ponderosa pine stand at Bluesky. In the upper portion of the crowns, 100 branches (10 to 15 per tree) were marked and sampled repeatedly throughout the study period. Losses of buds, conelets, and mature cones were described by cause and number for each of these stages. Four successive cone crops, maturing in 1953 through 1956, were measured four to seven times during each of their 2-year cone development periods.

Effects of Animals on Dispersed Seeds

From the time seeds are disseminated in the fall until they germinate the following spring they are available to a variety of mammals, birds, and invertebrates. To determine seed consumption during this 8-month period, the number of filled seeds remaining in the duff at the time of germination was subtracted from the number of filled seeds that fell. The amount of seedfall was determined from contents of seed traps, each of which had a surface area of 10.9 square feet. Duff samples adjacent to, and the same size as, the seed traps were removed to mineral soil in May each year, where the tree seeds were removed. This was accomplished by use of: 20 seed trap locations at Bluesky from 1948-1953 (except for 1952); five locations each at Dunn and Butler in 1951; 10 locations each at Dunn and Butler in 1953; and 10 locations at Dunn in 1954. Bluesky and Dunn had been partially cut but there had been no cutting at Butler.

To determine the species composition and relative abundance of the principal seed-eating mammals, the Bluesky area was snap-trapped for three nights twice annually--in the fall and in the spring--from 1948 to 1954. Common snap traps (using ponderosa pine seed, bacon, and rolled oats as bait) were set in groups of three at 20 stations in each of three rows. Stations were 25 feet apart. Feeding preferences of the small mammals were determined by Adams (1950) with stomach examinations.

RESULTS AND DISCUSSION

Several biological and physical factors drastically reduced the potential number of seeds available for animals, and they in turn further reduced the number available for germination. To illustrate this reduction of the seed crop, the results are presented in a time sequence, starting at the time of initial ovulate bud formation and ending just before seed germination. This 33-month period is diagramed to identify and show how the most important factors affected cone and seed survival throughout the sequence (fig. 1). The two important time segments emphasized in these discussions are: (a) before seed dispersal when red squirrels were the most important predator; and (b) after seed dispersal when ground-dwelling rodents were most important.

Effects of Animals on Cones

During the 4 cone years studied, only about one-fourth of the potential cones survived the first year of development (fig. 2). First-year cone survival ranged as high as 48 percent for the prospective 1956 crop and as low as 3 percent for the 1955 crop. Animals had little to do with this high mortality; abortions were primarily responsible, reducing the potential cone crop nearly two-thirds. Abortion rates ranged as high as 73 percent for the 1954 cone crop and as low as 21 percent for the 1956 crop. The causes of these extremely large and variable abortion rates were not determined.

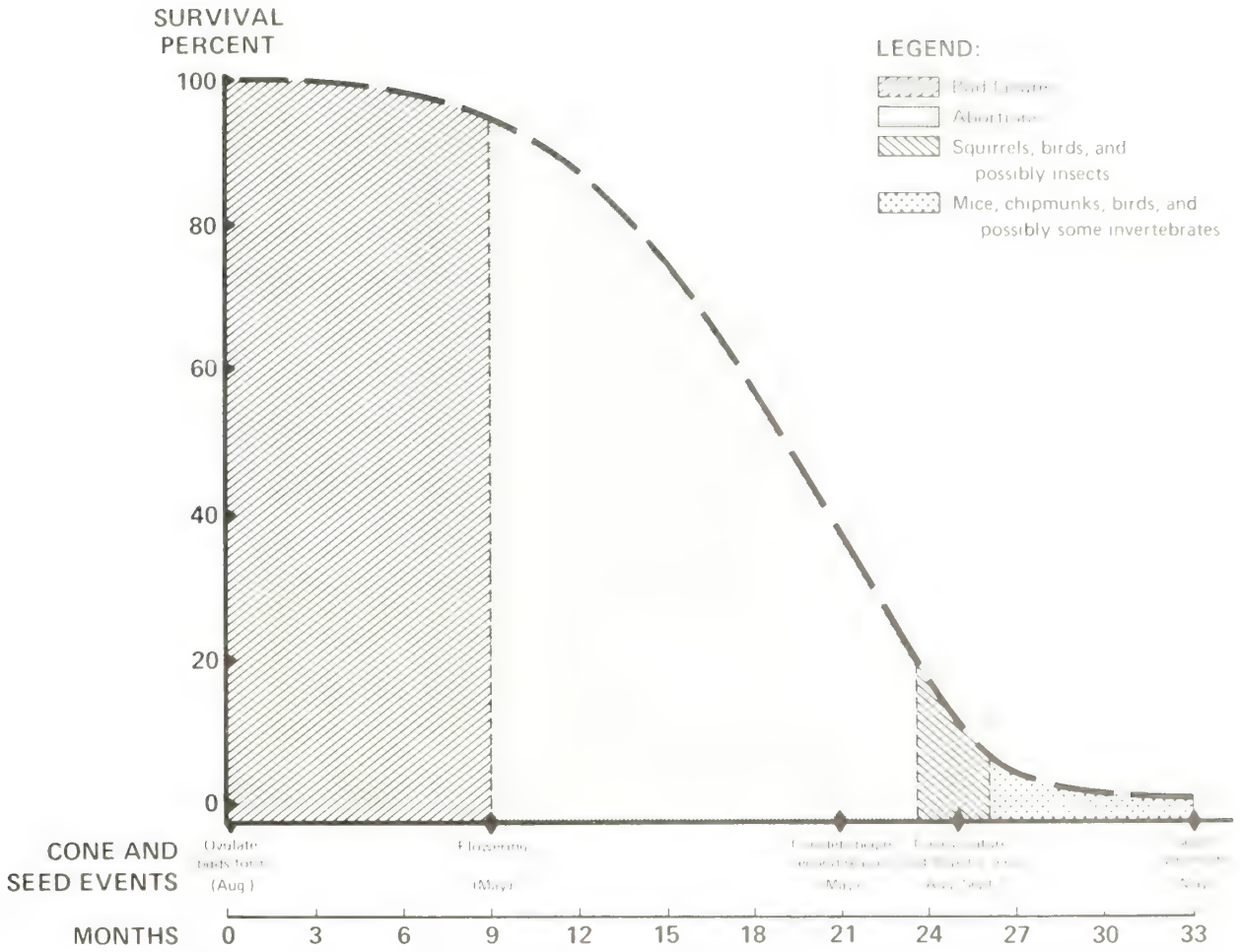

Figure 1.--Cone and seed development sequence of ponderosa pine and the most important factors affecting their survival during a 33-month period. Survival percent based on the potential seed crop present in the initial ovulate buds.

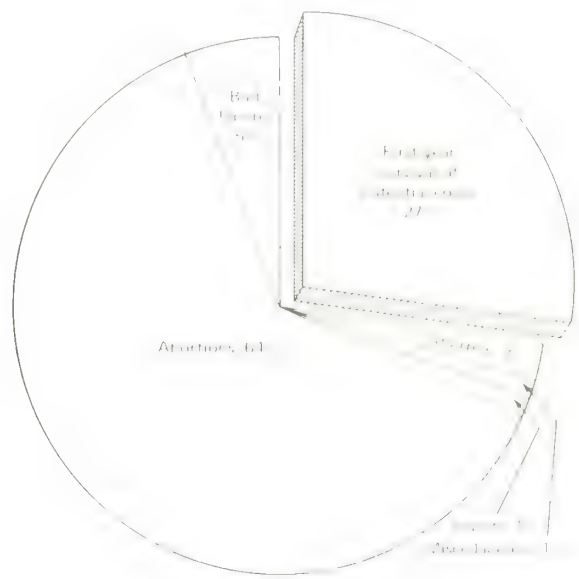

Figure 2.--Factors affecting the survival of ponderosa pine cones during their first year of development.

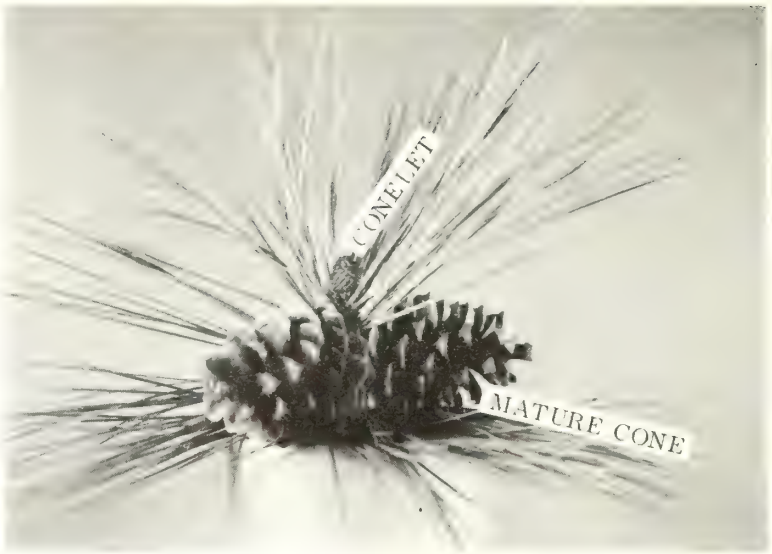

Figure 3.--Squirrels severed this ponderosa pine shoot to harvest the mature cones. The small conelet that would mature the next year, and the ovulate buds that would mature in 2 years (not shown here), are destroyed by such cutting.

First Year of Cone Development

Red squirrels were the only animals affecting the cones during the first year of cone development. These annual losses ranged from 0 to 8 percent, averaging less than 2 percent for the four cone crops. Because of the immaturity of the cones in the first year, it is unlikely the squirrels were specifically seeking them in their food forays. Rather, the cutting of immature cones was more likely due to their being located nearer the tip of the shoot beyond mature cones of the current season (Squillace 1953). In most cases, squirrels severed the entire cone-bearing shoots just below the current mature cone; thus, immature cones and ovulate buds were accidentally destroyed. Such indiscriminate cutting by the squirrels can adversely affect 3 years of cone production represented by the ovulate bud, immature cone, and mature cone (fig. 3). Squirrels also sever the ends of pine branches in the winter to feed on the cambium and, in the process, destroy some of the partially developed cones (Adams 1955).

Second Year of Cone Development

Of the cones that survived the first year of development, only about one-fourth survived the second year (fig. 4). Squirrels were responsible for most of the cone

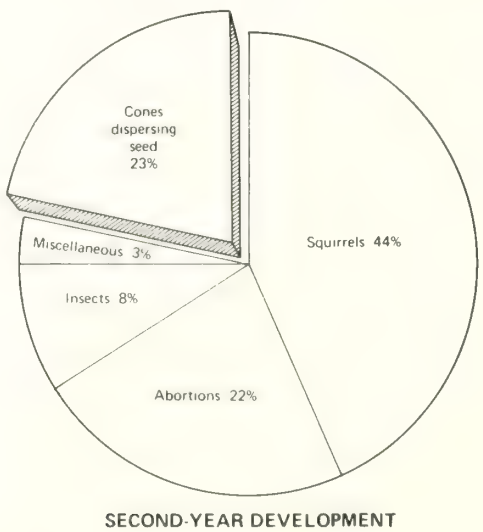

Figure 4.--Factors affecting the survival of ponderosa pine cones during their second year of development.

SCHMIDT, WYMAN C. and SHEARER, RAYMOND C.

1971. Ponderosa pine seed--for animals or trees, USDA Forest Serv. Res. Pap. INT-112, 11 p., illus.

Ponderosa pine seed development and survival studies in northwestern Montana showed that small forest animals reduced the potential seed crop very little during the 2-year cone development period but they consumed an average of 24 out of 25 pine seeds that matured. Red squirrels harvested an average of 66 of the mature cones; after the seeds were dispersed, deer mice, chipmunks, and birds consumed the equivalent of an additional 30 . Deer mouse populations apparently fluctuated in direct response to the size of the previous year's seed crop.

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reduction during this period; they cut nearly half of the cones. Yearly values, however, ranged from a low of 19 percent in 1954 to a high of 82 percent 2 years later, as shown by the following tabulation:

Cone year	*Number of cones*	*Percent cones harvested*
1953	128	54
1954	125	19
1955[1]	--	--
1956	49	82
Average	101	44

Previous squirrel-cutting records reported by Squillace (1953) were based on the number of *mature* cones available to the squirrels; consequently they were higher, as shown below:

Year	*Number of mature cones*	*Percent cones harvested*
1951	144	77
1952	9	89
1953	80	85
1954	80	30
1955[2]	--	--
1956	41	98
Average 1953-56		66
1951-56[3]		71

Squirrel-cutting patterns varied from year to year and were difficult to interpret. It was apparent that if mature cones were available, squirrels would harvest at least some of them. However, the amount of their cutting was not necessarily related to total size of the pine cone crop. The size of Douglas-fir cone crops appeared to influence the amount of squirrel-cutting activity in the pine. For example, in 1954, fir produced a heavy cone crop and squirrels cut only 19 percent of the pine cone crop. When the fir crop failed in 1956, the squirrels cut 82 percent of the light pine cone crop. In 1953, when fir produced a light crop, a more moderate percentage (54 percent) of the pine was cut. Seeds of Douglas-fir apparently constituted an important segment of the squirrel's diet.

Although the size of the Douglas-fir cone crop appeared to strongly influence the cutting in pine, other factors might have been involved. Halvorson's (1966) observations on Cedar Island, Flathead Lake, Montana, indicate that squirrels may harvest fewer cones in the moist, cool falls than they do in the dry, warm falls. The small percentage (19 percent) of pine cones harvested by squirrels in 1954, the moderate percentage (54 percent) in 1953, and the large percentage (82 percent) in 1956 support this observation; the fall of 1954 was moist and cool, the fall of 1953 was about average, and

---

[1]None of the cones that would have matured in 1955 survived the first season of development.

[2]No cones reached maturity in 1955.

[3]Includes Squillace's (1953) results.

the fall of 1956 was warm and dry. Thus, it is not entirely clear if weather conditions, size of the Douglas-fir crop or a combination of these two, abundance of other desirable foods, or other factors might have accounted for the annual differences in pine cone cutting by squirrels.

The period of squirrel cutting extended from mid-July to the period of maximum seed dissemination in September. During 1953, squirrels cut 15 percent of the crop before August 3. Most of the cones cut early in the season were used immediately, but the cones cut just before maximum seed dissemination were cached (Squillace 1953). Halvorson (1965) indicated that squirrels use cones from these caches over periods of 2 years or longer.

Abortions also reduced the number of surviving cones substantially during the second season of cone development. Even though the number of abortions dropped considerably from that in the first season, abortions still accounted for a surprisingly high 22 percent reduction over the 4 cone years studied--exceeding 10 percent every year when cones remained at the beginning of the second growing season.

Like squirrels, insects played a more important role in the second year than they did in the first year of cone development. Unidentified insects accounted for an average of 8 percent (ranging from 5 to 12 percent) of the mortality during the second season of cone development. Although not measured in these studies, birds and chipmunks probably harvested some seeds from the mature cones before the seeds were all disseminated.

Total Cone Development Period

Based on the total potential cone crop present in the original ovulate buds, only 6 percent of the cones survived the 2-year development period to disseminate seeds (fig. 5). Abortions were by far the most important limiting factor (70-percent reduction); most of this loss occurred in the first year. Squirrels were an important factor in the second season, but in relation to the total original potential they accounted for only 14 percent of the total reduction. Insects, bud failures, and other unidentified factors accounted for the remaining 10 percent of the reduction.

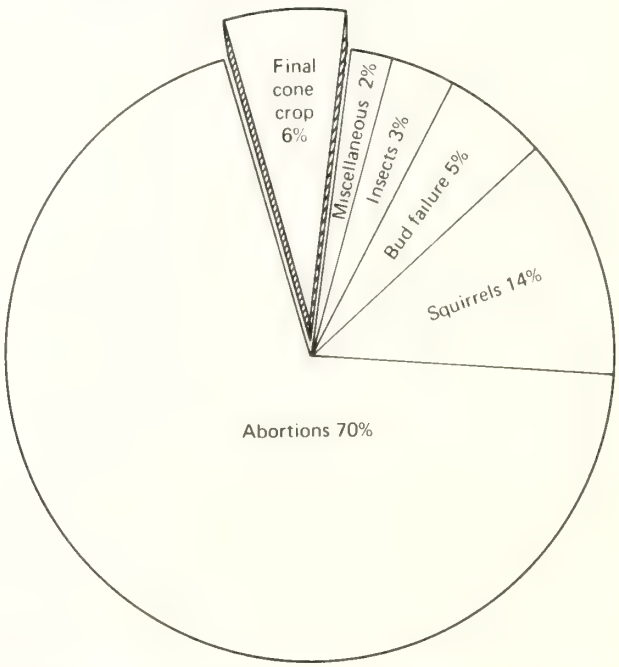

Figure 5.--Factors affecting the survival of ponderosa pine cones during their entire 2-year cone development period.

Table 1.--*Number of sound ponderosa pine and Douglas-fir seed dispersed and consumed per acre, by year, Kootenai National Forest (number of seeds given in thousands)*

Seed year[1]	Number of plots[2]	Ponderosa pine seed		Douglas-fir seed	
		Dispersed	Consumed[3]	Dispersed	Consumed
1948	20	75,400	69,600 (92)	3,000	1,800 (60)
1949	20	7,800	6,400 (82)	79,600	78,600 (99)
1950	20	0	0 --	3,900	3,900 (100)
1951	30	4,200	3,000 (71)	100	100 (100)
1952[4]	--	--	--	--	--
1953	39	7,100	6,300 (89)	10,400	9,200 (88)
1954	10	23,600	18,800 (80)	187,200	170,400 (91)
Total seed		118,100	104,100 (88)[5]	284,200	264,000 (93)

[1]1948-50 data were from Bluesky; 1951 and 1953 data from Bluesky, Butler, and Dunn; and 1954 data from Dunn.
[2]Quarter milacre in size.
[3]Values in percent shown in parentheses.
[4]No data taken.
[5]Average.

Effects of Animals on Dispersed Seeds

As soon as ponderosa pine and Douglas-fir seeds fell to the ground in early September, small animals began to eat or cache them. Regardless of the size of the seed crop available, they consistently consumed the majority of the filled seed, never taking less than 70 percent of the total number available. Over the 6-year study period, animals consumed about 90 percent of the pine and fir seeds before they could germinate in May (table 1). For example, 75,400 sound pine seeds and 3,000 sound fir seeds were dispersed per acre in 1948; this was a good seed crop year for pine but a poor one for fir. About 69,600 pine (92 percent) and 1,800 fir (60 percent) were consumed before May 1949 (Squillace and Adams 1950). The methods used did not separate bird and invertebrate feeding from that of the small mammals.

Of the mammals, deer mice apparently consumed most of the seed. They were 3 to 4 times more abundant than the combined total of all the other five species of small mammals found on the study area. In addition, stomach analyses of all small mammals on this study area by Adams (1950) indicated that only deer mice and chipmunks ate many seeds. Other small mammal species he found on the area included:

Longtailed meadow mouse (*Microtus longicaudus mordax* (Merriam))
Kootenai redbacked vole (*Clethrionomys gapperi saturatus* (Rhoads))
Rocky Mountain vole (*Phenacomys intermedius intermedius* (Merriam))
Gray shrew (*Sorex cinereus* (Kerr)).

Deer mouse populations apparently responded to the size of the previous year's pine and fir seed crop. Mice reproduce frequently and their population can respond rapidly to increased food supplies. Figure 6 supports this hypothesis when the average catch of these mice per 100 trap nights at Bluesky is compared with the pounds of conifer seed dispersed per acre the previous year. For example, from 1949 to 1950, the mouse population declined from nearly seven animals per 100 trap nights to less than three--similar in magnitude to the drop in seed crop from 1948 to 1949. In 1951, the mouse population reached its lowest point, probably because of the extremely small seed crops (both pine and fir) in 1950. A fair seed crop of pine in 1951 was followed by a recovery in the numbers of mice caught in 1952. The 1952 conifer seed crop was poor; however, the mouse population did increase in 1953. Heavy crops of other desirable foods might have been available that year.

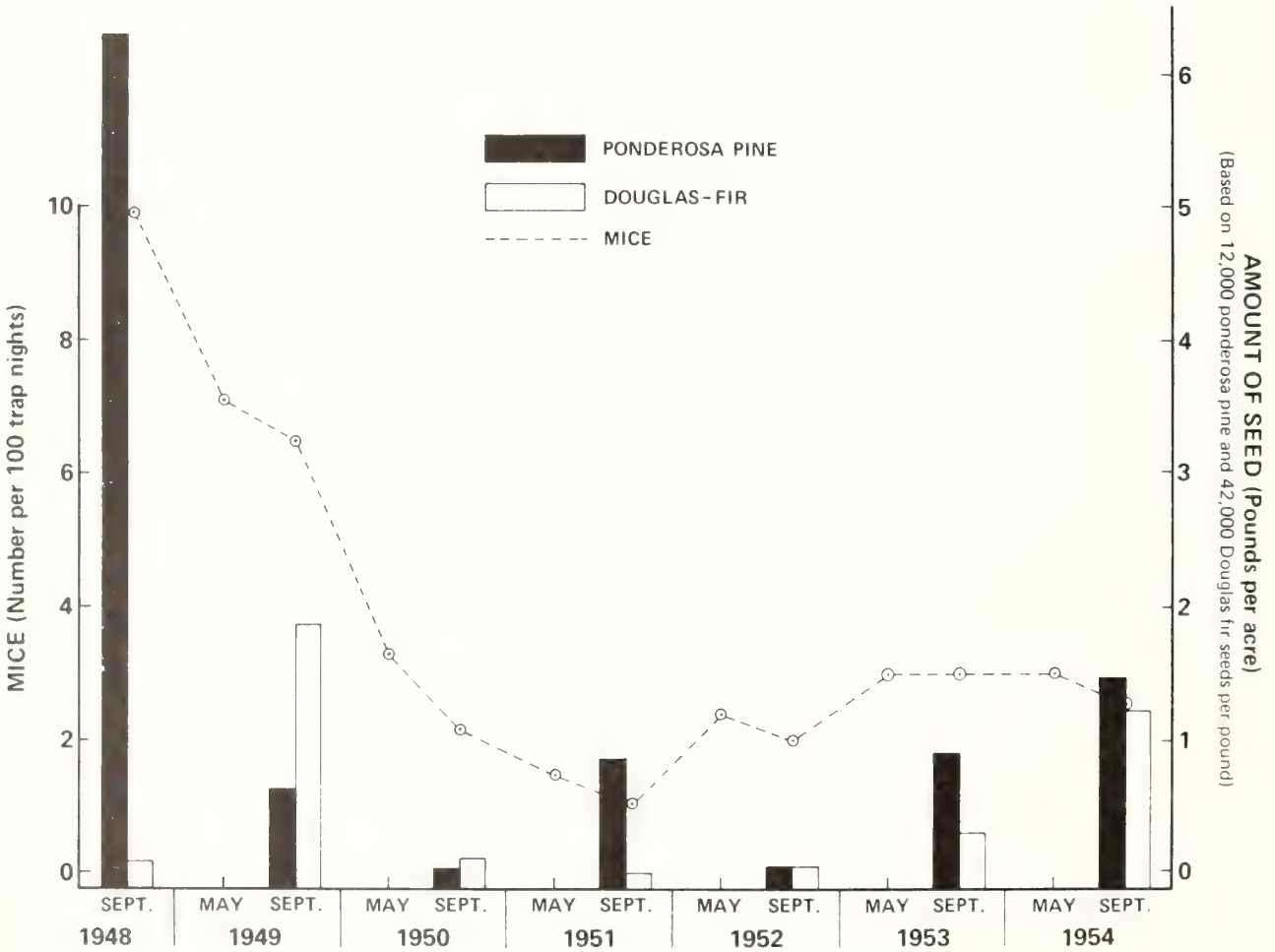

Figure 6.--Comparison of the number of mice trapped per 100 trap nights and the amount of seed dispersed per acre, Kootenai National Forest, 1948-1954.

CONCLUSIONS

Most ponderosa pine seeds that reach maturity are eaten by animals. Out of 25 seeds that reach maturity, 24 provide one of the sources of energy for the small forest animals; the single remaining seed is available for germination.

Red squirrels, chipmunks, and birds have first chance at harvesting mature seeds in the cone. Ground dwelling mammals, ground feeding birds, and invertebrates must search for the seed remaining on the forest floor. Squirrels have a survival advantage in that they can cache cones from a good cone crop and keep them in storage for 2 years or longer, while the other small mammals and birds must use the current supply of seed before it germinates in the spring.

Pine and fir seeds constitute an important part of the diet of the small animals inhabiting these forests. How much food in the form of tree seeds does a mature ponderosa pine--Douglas-fir forest produce? On a per-tree basis, mature ponderosa pine trees under natural forest conditions produce about 125 cones per tree and about 60 sound seeds per cone in a moderate seed year--nearly two-thirds of a pound per tree.

If by chance a fair seed crop year for both pine and fir occurs concurrently in the forests of northwestern Montana, approximately 2 pounds of sound pine seed per acre (24,000 seeds) and about 2 pounds of sound fir seed per acre (84,000 seeds) might mature. Of this 4 pounds, squirrels and cone-feeding birds eat or cache about 2.8 pounds, and 1.2 pounds are dispersed, of which small mammals and birds consume about 1.1 pounds. Thus, about 0.1 pound (about 600 pine and 2,100 fir seeds) is available for tree regeneration. A good seed crop of both species concurrently would about triple these amounts. However, good seed crops of both species are infrequent (about every 3 to 5 years) and they seldom occur in the same year; thus, the total amount of conifer seed available annually for animals would seldom exceed the total amounts described above for a fair seed crop year.

Because chipmunks cache some ponderosa pine seeds they never recover, the amount consumed might be slightly less and the amount available for germination might be somewhat greater than indicated. West (1968) found that up to 15 percent of the ponderosa pine seedlings in central Oregon resulted from seed caches not consumed by the animals.

Although animals play the most obvious dramatic role in seed production, they act only during the last 9 or 10 months of a 33-month cycle that terminates at the beginning of seed germination. During the 2 years prior to germination, the seed users are far overshadowed in importance by more subtle factors. Large potential cone crops are drastically reduced by abortions; thus a population explosion of trees is prevented long before animals begin harvesting the seeds. However, after the seeds mature, animals become very important and efficiently utilize this available food, as shown in the following tabulation:

Description	*Percent*	*Number*
Seeds reaching maturity		100
Seeds used by animals before dispersal	66	66
Seeds dispersed		34
Seeds used by animals after dispersal	88	30
Seeds available for germination		4

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MAXIMUM PEAK FLOWS FOR SELECTED RETURN PERIODS FOR WATERSHEDS WEST OF THE CONTINENTAL DIVIDE IN IDAHO AND MONTANA

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ABSTRACT

The long-term average water yield of a watershed appears to be a good index to the magnitude of its expected peak flow. On the basis of this relation, tables are presented showing expected peak flows that are applicable to watersheds in Idaho and Montana west of the Continental Divide. Tabulated peak flows are for four different return periods: mean annual; 5; 10; and 20 years. Three examples are given to illustrate the tables' field application.

What is the 20-year flood potential of this watershed?

INTRODUCTION

Foresters and other land managers have long considered water an important product of forest lands. This product yields great benefits when its flow is orderly, timely, and is confined within the banks of a stream. On the other hand, water appearing as a flood is a potentially destructive force that land managers should consider when planning future forest operations.

The effects of clearcutting operations on the hydrologic regime of a watershed are complex, and the magnitude of these effects is highly variable. Nevertheless, we do know that a clearcut watershed yields more water (Hibbert 1967), and that the pattern of runoff distribution is changed, including an increase in base flow and peak flow (Bethlahmy 1971). Thus, foresters and other land managers who contemplate clearcutting operations should consider the associated problem of future changes in the hydrologic regime.

Our research has shown that on a unit area basis the long-term average water yield of a watershed is a good index to the magnitude of its expected peak flow. The greater the average yield per unit area, the greater the expected peak flow for period of record. This relation is readily perceived from table 1 that shows data for 11 rivers in Idaho which have good or excellent streamflow records (U.S. Department of Interior 1964). Notice the regular decrease in values of both average annual flow and associated peak flow. Although peak flow per unit area is related to unit drainage yield, any discussion of peak flow should include the element of chance. A record of many years of data will probably include greater peak flow values than a short record. Hence, a comparison of peak flows for different areas should be based not only on the watershed's average yields but also on the element of time; how long is the record, and how often can one expect a peak flow of a given magnitude? Such considerations are especially important to engineers and economists who are concerned with investments in structures having an economic life expectancy.

Table 1.--*Relation of peak flow to average annual flow for some Idaho rivers with good or excellent stream records*

River	Average annual flow	Peak flow[1]	Elevation of gage	Length of record	Watershed area
	[2]*C.f.s.m.*	[2]*C.f.s.m.*	[3]*Feet*	*Years*	*Sq.mi.*
Cub	4.24	36.86	5,320	21	19.4
Boundary	1.98	33.81	1,770	34	97
Mission	1.71	22.96	2,800	6	23
Clearwater (Kamiah)	1.68	21.24	1,162	54	4,850
Moyie (Eastport)	1.23	18.60	2,620	35	570
Yaak	1.20	15.80	1,850	8	766
Moyie (Eileen)	1.16	14.57	2,124	39	755
Big Lost River (Wild Horse)	.86	11.14	6,820	20	114
Robie	.50	10.32	4,960	14	15.8
Thomas Fork	.44	7.69	6,280	15	113
Bannock	.36	5.91	5,240	16	5.75

[1]Peak flow for period of record.
[2]Cubic feet per second per square mile.
[3]Above mean sea level.

Peak flows which can be expected in Idaho and Montana, in watersheds west of the Continental Divide, are listed in tables 2 and 3 for four different return periods. The selected return periods are: 2.33 years (usually termed the mean annual return period); 5; 10; and 20 years. In these tables, peak flow is a function of average water yield and an expected return period, and is expressed in units of cubic feet per second per square mile (c.f.s.m.). In table 2, average water yield (the independent variable) increases by selected increments in inches, and in table 3 by selected increments in c.f.s.m. These tables were constructed in accordance with the methods described in Appendix 1, and are based on sources of data listed in Appendix 2.

Table 2.--*Maximum peak flows (c.f.s.m.) for selected return periods for watersheds west of the Continental Divide in Idaho and Montana*

Average annual yield	Return period (years)			
	2.33	5.0	10	20
Inches	*C.f.s.m.*			
5.0	2.6105	3.2904	4.1589	5.2339
6.0	2.9845	3.7810	4.7295	5.9284
7.0	3.3984	4.3267	5.3577	6.6899
8.0	3.8526	4.9282	6.0433	7.5180
9.0	4.3465	5.5856	6.7854	8.4111
10.0	4.8791	6.2975	7.5818	9.3661
11.0	5.4484	7.0619	8.4294	10.3791
12.0	6.0520	7.8755	9.3240	11.4450
13.0	6.6866	8.7343	10.2609	12.5578
14.0	7.3487	9.6336	11.2345	13.7109
15.0	8.0341	10.5679	12.2388	14.8972
16.0	8.3787	11.5314	13.2676	16.1092
17.0	9.4580	12.5180	14.3145	17.3395
18.0	10.1875	13.5216	15.3730	18.5808
19.0	10.9229	14.5361	16.4370	19.8258
20.0	11.6600	15.5554	17.5005	21.0677
21.0	12.3948	16.5741	18.5581	22.3004
22.0	13.1236	17.5867	19.6047	23.5181
23.0	13.8431	18.5885	20.6356	24.7157
24.0	14.5503	19.5751	21.6467	25.8885
25.0	15.2426	20.5426	22.6346	27.0356
26.0	15.9176	21.4877	23.5963	28.1450
27.0	16.5736	22.4075	24.5291	29.2226
28.0	17.2089	23.2997	25.4313	30.2636
29.0	17.8224	24.1624	26.3011	31.2663
30.0	18.4131	24.9941	27.1375	32.2294
31.0	18.9804	25.7938	27.9398	33.1524
32.0	19.5239	26.5609	28.7075	34.0348
33.0	20.0434	27.2948	29.4406	34.8767
34.0	20.5390	27.9956	30.1391	35.6784
35.0	21.0108	28.6634	30.8036	36.4404
36.0	21.4592	29.2985	31.4345	37.1635
37.0	21.8846	29.9016	32.0326	37.8485
38.0	22.2876	30.4734	32.5988	38.4967
39.0	22.6689	31.0146	33.1341	39.1092
40.0	23.0291	31.5263	33.6394	39.6871
41.0	23.3690	32.0094	34.1159	40.2318
42.0	23.6893	32.4649	34.5648	40.7447
43.0	23.9910	32.8941	34.9873	41.2272
44.0	24.2747	33.2979	35.3845	41.6807
45.0	24.5413	33.6776	35.7575	42.1065
46.0	24.7917	34.0343	36.1077	42.5061
47.0	25.0266	34.3690	36.4361	42.8807
48.0	25.2469	34.6830	36.7440	43.2317
49.0	25.4532	34.9774	37.0323	43.5605
50.0	25.6465	35.2530	37.3022	43.8681

Table 3.--*Maximum peak flows (c.f.s.m.) for selected return periods for watersheds west of the Continental Divide in Idaho and Montana*

Average annual yield	Return period (years)			
	2.33	5.0	10	20
	C.f.s.m.			
0.2	1.8989	2.3648	3.0639	3.8924
0.3	2.2982	2.8829	3.6801	4.6489
0.4	2.7664	3.4946	4.3972	5.5242
0.5	3.3070	4.2059	5.2192	6.5222
0.6	3.9216	5.0199	6.1472	7.6432
0.7	4.6092	5.9363	7.1786	8.8830
0.8	5.3663	6.9514	8.3073	10.2335
0.9	6.1871	8.0581	9.5239	11.6827
1.0	7.0638	9.2462	10.8160	13.2157
1.1	7.9868	10.5032	12.1695	14.8154
1.2	8.9455	11.8146	13.5689	16.4635
1.3	9.9289	13.1654	14.9980	18.1414
1.4	10.9259	14.5402	16.4414	19.8309
1.5	11.9261	15.9241	17.8839	21.5148
1.6	12.9196	17.3031	19.3120	23.1778
1.7	13.8976	18.6645	20.7135	24.8062
1.8	14.8526	19.9974	22.0783	26.3886
1.9	15.7782	21.2924	23.3978	27.9155
2.0	16.6694	22.5419	24.6652	29.3798
2.1	17.5222	23.7401	25.8756	30.7759
2.2	18.3339	24.8825	27.0254	32.1004
2.3	19.1026	25.9662	28.1124	33.3509
2.4	19.8273	26.9894	29.1358	34.5267
2.5	20.5079	27.9516	30.0954	35.6282
2.6	21.1447	28.8530	30.9921	36.6565
2.7	21.7386	29.6946	31.8274	37.6136
2.8	22.2908	30.4779	32.6033	38.5018
2.9	22.8030	31.2051	33.3222	39.3244
3.0	23.2768	31.8783	33.9867	40.0841
3.1	23.7143	32.5004	34.5997	40.7846
3.2	24.1173	33.0739	35.1642	41.4292
3.3	24.4881	33.6018	35.6830	42.0215
3.4	24.8286	34.0868	36.1592	42.5649
3.5	25.1407	34.5317	36.5957	43.0626
3.6	25.4267	34.9395	36.9952	43.5182
3.7	25.6882	35.3126	37.3605	43.9346
3.8	25.9273	35.6537	37.6942	44.3148
3.9	26.1454	35.9652	37.9987	44.6617
4.0	26.3445	36.2494	38.2765	44.9781
4.1	26.5259	36.5086	38.5295	45.2662
4.2	26.6911	36.7446	38.7599	45.5285
4.3	26.8415	36.9595	38.9696	45.7672
4.4	26.9784	37.1552	39.1604	45.9842
4.5	27.1028	37.3330	39.3338	46.1816
4.6	27.2159	37.4947	39.4913	46.3608
4.7	27.3186	37.6416	39.6344	46.5236

BETHLAHMY, NEDAVIA

1971. Maximum peak flows for selected return periods for watersheds west of the Continental Divide in Idaho and Montana, USDA Forest Serv. Res. Pap. INT-113, 12 p., illus.

Peak flow tables are presented that are applicable to watersheds in Idaho and Montana west of the Continental Divide. The tables show peak flows as a function of mean annual water yield, and are for four different return periods: mean annual; 5; 10; and 20 years. Three examples illustrate the practical use of the tables.

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A mountain stream at flood stage.

EXAMPLES FOR FIELD APPLICATION

Three examples are given to show how the tables can be used for field application.

EXAMPLE 1

Problem: A road will be built across the outlet of a 1.5-sq.-mi. drainage having an expected annual water yield of 40 inches. What is the maximum rate of flow the culvert should accommodate:

(a) if designed for a 20-year flood?
(b) if designed for a 50-year flood?

Solution:

(a) For an annual yield of 40 inches, table 2, col. 5, shows a peak flow of 39.69 c.f.s.m. Since the drainage area is 1.5 sq. mi., we can expect a 20-year flood of 59.53 c.f.s. (39.69 X 1.5).

(b) The tables do not show peak flows for return periods exceeding 20 years. Extrapolation is required, but this procedure is fraught with great uncertainty. In table 2, opposite an average 40-inch annual yield, we find the expected peak flows for the 10- and 20-year floods to be 33.64 and 39.69 c.f.s.m., respectively. Plot the paired values (year versus flow) on log-log paper, connect them with a straight line, and extend the line to the 50-year flood. The peak flow is 49.3 c.f.s.m. Inasmuch as the area is 1.5 sq. mi., the expected 50-year flood is 74 c.f.s. (49.3 X 1.5 = 74).

It must be understood that such extrapolation results in only approximate values.

EXAMPLE 2

Problem: A road crosses the outlet of a 40-acre watershed over a 12-inch corrugated metal culvert whose top is 1 foot below the road surface. Plans call for clearcutting the watershed that has an annual yield of 35 inches. After cutting we expect annual water yield to increase by 15 percent. Assuming a 20-year-design flood, will the presently located culvert accommodate the increased flow?

Solution:

The expected annual flow is 40.25 inches (35 inches X 1.15). In table 2, col. 5, interpolating for peak values between 40 and 41 inches, we obtain an expected peak flow of 39.82 c.f.s.m. Since the area involved is 40 acres, the expected peak flow is 2.49 c.f.s. $(39.82 \times \frac{40}{640})$. Using culvert discharge tables (e.g., Hendrickson 1957), we find that the presently installed culvert (use 1.0 percent slope and 0.025 roughness coefficient) will accommodate only 2.4 c.f.s. Because there is a present capacity of only 2.4 c.f.s., and the expected need is for 2.49 c.f.s., it appears that the road will probably be damaged by overflowing unless a larger culvert is installed or the surface of the road is raised to allow for ponding.

EXAMPLE 3

Problem: The annual water yield from a 5.0-sq.-mi. drainage is 40 inches. Plans call for clearcutting a 40-acre subwatershed. What are the present and expected peak flows at the outlet of the main drainage for a 10-year flood if the annual water yield of the clearcut area is expected to increase by 15 percent?

Solution:

Under present conditions (before cutting) the expected 10-year flood for the entire drainage is 168.20 c.f.s. In table 2, col. 4, opposite 40 inches, read 33.64 c.f.s.m. and multiply by 5.0 sq. mi., and for the 40-acre subwatershed it is 2.10 c.f.s. $(33.64 \times \frac{40}{640})$.

After cutting, the average yield from the clearcut 40-acre subwatershed will be 46.0 inches (40 X 1.15). In table 2, col. 4, we read a peak flow value of 36.11 c.f.s.m. Since the subwatershed is 40 acres, the peak flow is 2.26 c.f.s. $(36.11 \times \frac{40}{640})$.

On the clearcut area, the peak flow will increase by 0.16 c.f.s. (2.26 - 2.10). Add this value to the precutting peak flow for the entire drainage:

$$168.20 + 0.16 = 168.36 \text{ c.f.s.}$$

It is apparent that clearcutting the 40-acre subwatershed will not alter the peak flow of the main watershed in any significant way.

A raging mountain stream overflows a bridge.

DISCUSSION

The three examples illustrate how the tables may be used, and the practical significance of the effects of clearcutting operations. We once again remind the reader that the tabulated values are expressed in yield per unit area, and hence may be applied to watersheds of any size or at any elevation.

In illustrating the use of the tables, we used a potential water yield increase of 15 percent. Some readers may consider this figure as too conservative, because it is considerably smaller than figures reported in the literature. At Fraser, Colorado, for example, where 75 percent of the annual precipitation occurs as snow, a 40-percent commercial clearcut in strips yielded a first-year increase of 30 percent in annual streamflow (Goodell 1958). We used the figure 15 percent as an example, and not as a universal recommendation. In using the tables, the reader should consider the special circumstances applying to his case.

The tables may also be used to solve problems relating to channel stability, bank cutting, and stream level. However, because the characteristics of stream channels vary considerably from one segment to another, it is apparent that a particular problem may not have a unique solution. Nevertheless, the land manager may sometimes be particularly concerned with certain segments of a stream channel because they appear vulnerable to changes in the hydrologic regime. In such cases, it may be worthwhile to make the assumptions needed to perform the calculations and to determine the magnitude of changes that can be expected.

Limitations

Flood peaks reflect the complex interaction of many variables, and many formulas have been devised to account for the effects of these variables. In most cases, however, the land manager has only limited information about the magnitude of the important variables. For example, Rosa (1968) published water yield maps for Idaho, but maps of this sort are not available for even such basic variables as rainfall intensity or soils grouped according to their hydrologic properties.

The user of these tables is cautioned that the tabulated values are far from being definitive; they are only an approximation to give the land manager an idea of what may be expected. Mr. C. A. Thomas has observed[1] that the tabulated values may be too high for streams with a high base flow and are probably too low for streams with flashy runoff and low base flows.

The user should bear in mind that the tables will probably be applied to areas considerably smaller than those from which the tables were derived. Furthermore, flow data for the very small drainages cover only a brief span of time.

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[1]Personal communication, on file at Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Moscow, Idaho.

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APPENDIX I

The published tables are based on the finding that peak flow is a function of mean water yield. The equation is:

$$\ln (P/A) = a+b\ [1.5708 - \text{arc tan } (\sinh F/A)] \qquad (1)$$

in which P, A, and F are, respectively, peak flow (c.f.s.), area (square miles), and mean flow (c.f.s.). The constant 1.5708 is the angle 90° expressed in radians.

Equation (1) is based on data found in Thomas, Broom, and Cummans (1963) and Bodhaine and Thomas (1964). Only those rivers were analyzed whose records indicated no diversions, impoundments, or poor data. The equation was derived as follows: For each streamflow record, the annual peak flow data were arranged in a descending order of magnitude. If N represents the total number of items in the series, and M_i is the ordered position in the series (i.e., 1,2...M_i...N), then the probability of occurrence (P_r) (or percent chance) for a peak flow equal to or smaller than that in ordered position M_i is

$$100 \times \frac{(M_i - 0.5)}{N}$$

This probability was calculated for each ordered position, and defined the plotting position of the associated peak flow on log-normal paper. A smooth line was drawn through the plotted data, but was not extended beyond the range of the plotted data. We then read the adjusted peak flows for the selected recurrence periods: 2.33; 5; 10; and 20 years. (The recurrence period is 100 divided by the probability of occurrence; e.g., if $P_r = 20$, $T_r = 5$.)

Data drawn from the smooth curves formed four new sets of data, one for each selected recurrence period. Each set of data was then analyzed to obtain the values of a and b in equation (1). We have listed below these values, as well as the correlation coefficient (R) relating the dependent and independent variables.

Recurrence period (Years)	a	b	R
2.33	3.3434	-1.9693	0.966
5	3.6653	-2.0440	.950
10	3.7141	-1.8908	.938
20	3.8733	-1.8324	.902

Values for tables 1 and 2 were calculated for selected values of mean flow (F/A) using the equation

$$\frac{P}{A} = e^{a+b[1.5708 - \text{arc tan } (\sinh \frac{F}{A})]} \qquad (2)$$

where e is 2.71828, base for Naperian logarithms.

APPENDIX II

Data for the following rivers were used to derive equation 1.

River No. (USGS)	River name and location	Length of record	Area	Mean elevation
		Years	*Sq.mi.*	*Feet*
	IDAHO			
12-3055	Boulder Creek near Leonia	37	53	4,980
12-3065	Moyie River at Eastport	36	570	4,870
12-3075	Moyie River at Eileen	40	755	4,710
12-4110	Coeur d'Alene River near Prichard	14	335	4,120
12-4130	Coeur d'Alene River at Enaville	26	895	3,610
13-3170	Salmon River at White Bird	53	13,550	6,720
13-3375	South Fork Clearwater River at Elk City	21	261	5,150
13-3390	Clearwater River at Kamiah	55	4,850	5,010
13-3405	North Fork Clearwater River at Bungalow Ranger Station	13	996	4,930
13-1200	Big Lost River at Wildhorse, near Chilly	21	114	8,540
13-1625	East Fork Jarbridge River near Three Creek	16	89	7,600
13-1850	Boise River near Twin Springs	54	830	6,350
13-1965	Bannock Creek near Idaho City	17	5.75	5,240
	WYOMING			
13-115	Pacific Creek near Moran	21	160	8,160
13-320	Bear Creek near Irwin	12	77.1	7,130
	MONTANA			
3505	Kootenai Creek near Stevensville	7	28.9	6,670
3560	Skyland Creek near Essex	6	8.09	5,920
3585	Middle Fork Flathead River near West Glacier	18	1,128	5,800
3590	South Fork Flathead River at Spotted Bear	10	958	6,130
3595	Spotted Bear River near Hungry Horse	8	184	5,960
3600	Twin Creek near Hungry Horse	8	47	5,300
3610	Sullivan Creek near Hungry Horse	9	71.3	5,510
3615	Graves Creek near Hungry Horse	9	27	5,430

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THE RELEASE OF WATER FROM FOREST SNOWPACKS DURING WINTER

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THE RELEASE OF WATER FROM FOREST SNOWPACKS DURING WINTER

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ABSTRACT

In the northern Rocky Mountains, in Idaho, data collected during three winters demonstrate why there is always less snow beneath the canopy of a cedar-hemlock forest than in the adjacent small openings. The author presents as evidence the differential release of water, which originates in the canopy as throughfall-drip, thus accounting for part of the deficiency in snow water equivalent beneath the canopy by April 1. Such informative data were made possible by a new instrument designed to collect waterflow from the snowpack.

INTRODUCTION

parisons of the amounts of snow on the ground almost invariably show less snow under the crowns than in the adjacent opening; but, according to Hoover (1) this leaves unanswered the following questions:

(a) Is the deficiency of accumulated snow in the forest a result of evaporation of snow from tree crowns?

(b) Was intercepted snow blown off the tree crowns and redeposited into the opening?

(c) Or did the wind eddies caused by the surrounding tree crowns deposit excess snow in the opening and, conversely, deposit less in the forest?

Surprisingly, after one hundred years of research, there remains a deficiency of basic data to answer these questions and a lack of suitable instruments for resolving the problem (7).

We are looking at this problem from a new point of view--the base of the snowpack. At the Priest River Experimental Forest (latitude 48°21'N., longitude 116°47'W.) in the northern Rocky Mountains, in Idaho, we have asked the question: Is the deficiency of snow in the forest a result of greater release of water from the snow mantle beneath the tree crowns? As a partial answer, this report describes a new instrument designed to collect outflow from the snowpack; and it also summarizes data on the releases of water in the undisturbed forest and small openings on two slope aspects over a 3-year period. We offer as evidence the differential release of water as accounting for part of the deficiency in snow water equivalent beneath the canopy by April 1.

This investigation is part of continuing research being conducted by the USDA Forest Service to develop management systems for the mountainous forests in the West where winter snowfall provides much of the water.

STUDY METHODS

The study area lies between 4,000 and 5,000 feet elevation in the rugged, upper portion of the Priest River Experimental Forest. The area is divided into north and south aspects by a sharp-crested ridge, which extends 1,200 feet higher to the summit of the Selkirk Mountain range. The forest ecosystem is comprised predominantly of western hemlock (*Tsuga heterophylla* (Raf.) Sarq.), western white pine (*Pinus monticola* Dougl.), and western redcedar (*Thuja plicata* Donn.), undisturbed by man and mature in age (fig. 1). Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western larch (*Larix occidentalis* Nutt.) and Engelmann spruce (*Picea engelmannii* Parry) are intermingled but subordinate in volume on the moist north aspect. On the drier south aspect, western hemlock and western redcedar are usually missing from the mixture and Douglas-fir assumes a dominant role. The general canopy is 120 to 140 feet tall and very dense on the north aspect; it is 20 to 30 feet shorter and more open on the drier south aspect.

Influenced by the Pacific Ocean, the winters are cool and wet and the summers dry. Winter temperatures are less severe than in the higher elevations of the Rocky Mountains. Storm-bearing winds usually sweep in from the southwest. Occasionally, during the winter a continental storm will come from the east and northeast. Year-long precipitation averages over 40 inches.

Instrumentation.--During the planning stage, we were confronted with the lack of a suitable instrument to measure directly the outflow from beneath a snowpack. The problem was solved by designing a snow lysimeter based on a concept used earlier by the Corps of Engineers at the Central Sierra Snow Laboratory (9).

The snow lysimeter collects outflow in a ground-level pan (fig. 2) from an undisturbed, finite column of snow deposited in place (fig. 3). A thin layer of polyethylene encloses the column of snow and prevents lateral flow from entering the lysimeter. (The cross-sectional area of the column and pan is 2.7 sq. ft.) As the effluent drains into a catchment tank it is monitored continuously by a water level recorder. The outflow, depending upon the nature of the storm or thawing condition, represents an integrated measure of rain, throughfall-drip, and snowmelt percolate. The installation and routine operation of the lysimeter are more fully described elsewhere (2,3).

Figure 1.--Cedar-hemlock eco-[illegible] Station 47.

In this study, six lysimeter stations are grouped in pairs as follows: station 39 adjacent to station 40 and station 45 adjacent to station 42, both pairs situated on the north aspect; and station 49 adjacent to station 47 on the south aspect. A distance no greater than 300 feet separates the stations in each pair. The three pairs were placed into operation in 1967, 1968, and 1969 in the order mentioned. In relation to forest cover, station 39 is located in the northeast quadrant of a small, manmade clearing; stations 45 and 49 are situated midway across long, 50-foot-wide clearcut strips. These stations represent the situation termed "small opening." The "forest condition" includes stations 40, 42, and 47 positioned well into the undisturbed forest. These stations lie within the drip zone of a major tree species but away from the annular zone of the tree bole. Other descriptive details of each lysimeter station appear in table 1.

Weather stations provide precipitation and temperature data to complement the lysimeter information. Each weather station is mounted on an elevated platform (fig. 4), situated near the lysimeter. In the forest, the weather station is located underneath a tree with a canopy configuration similar to that over the lysimeter; in the small opening, the station is nearly the same distance from the bordering trees as is the lysimeter.

The precipitation instruments are incapable of separating rain from snow; therefore, observed rainfall (in the small opening) is determined indirectly by comparing the catch of precipitation with ambient air temperature recorded in a standard (ventilated) shelter. It is assumed that rain occurs if the temperature is greater than 33° F. There are exceptions when snow falls during a storm, although the temperature indicates rain or vice versa.

[illegible] with rod-frame, sliding collar, and polyethylene bag attached. Inclination of collar is parallel to angle of ground surface.

Figure 3.--Lysimeter station 42 shows a snow column depth of approximately 43 inches (measured March 31, 1971). Completely hidden is the thin layer of polyethylene which separates the snow column from the surrounding snowpack.

Figure 4.--Weather station 45, shown mounted to a culvert pipe which provides entry to the catchment tank of lysimeter station 45.

Table 1. -

Lysimeter station	Aspect	Elevation	Slope	Description of station site		Distance to nearest tree crown
				opening	Undisturbed forest	
40	N	4,000			Range of dominant tree heights, 120-; closure, 90-	
39		4,000	30	Circular-shaped clearing, diameter averages 100 feet		14
42	N	4,300	48		Range of dominant tree heights, 120-140 feet; crown closure, 90-100%	
45	N	4,300	38	Clearcut strip, 50 by 600 feet, long-axis oriented N-S		
47		4,600	44		Range of dominant tree heights, 90-100 feet; crown closure, 20-30%	
49		4,600	31	Clearcut-strip, 50 by 650 feet, long-axi oriented N-S		25

the rate of snow catch in the precipitation gage in the forest with the rate measured in the small opening. A rapid rate of catch in the small opening occurring simultaneously with a substantial reduced rate of catch in the forest indicates that the trees are loading. If little or no snow slides off the canopy into the precipitation gage between storms, it is assumed the canopy is retaining its snow load. This documental evidence is partially confirmed by weekly visits to the sites.

The lysimeter and weather stations are operated continuously through the accretion (winter) and ablation (spring) periods. This paper will deal only with the winter period; November-March, inclusive, on the north aspect and November-January, inclusive, on the south aspect. In 1970, the spring season on the south aspect began in February.

Data analysis.--Computation of the total volume of outflow for the lysimeter represents a straightforward summation of instantaneous hourly flow rates converted to area-inches.

A more complex analysis involves the partitioning of outflow into its components of origin--*rain percolate* (in the small opening), *throughfall-drip percolate* (in the forest), and *snowmelt percolate* from the snowpack proper. This analysis is based primarily upon a number of generalized assumptions dealing with the disposition of rainfall, throughfall, and drip that occur during and after storms. The entire scheme is undergoing refinement; the approach presented in this paper is an earlier version and has certain limitations that will be discussed subsequently.

The partitioning of outflow in the small opening depends upon the amount of observed rainfall. If outflow is equal to or less than observed rainfall, it is defined as rain percolate. Excess outflow, or that which exceeds the observed rainfall, is called snowmelt percolate. In a sheltered opening, such as found on the north aspect, the gage rainfall catch represents a realistic estimate of the amount of rain that actually infiltrates the snowpack. In a windblown opening, on the south aspect, the gage rainfall catch measured less than that which actually reaches the snow surface. Thus, the snowmelt percolate portion of the outflow is very likely an overestimation.

The separation of outflow in the forest hinges first on two basic assumptions: (a) That the amount of rainfall observed in the opening is the same amount as the rainfall incident on the canopy; and (b) that a small portion of rainfall (about 20 percent) is intercepted by the canopy and lost for the duration of the storm. The larger portion of rainfall that is not intercepted is defined as throughfall.

Throughfall-drip percolate includes the following: (a) Throughfall from a canopy bare of snow which in turn percolates through the snowpack into the lysimeter; (b) drip from melting snow held in the canopy during a storm-free period which in turn percolates through the snowpack; or (c) combined throughfall and drip during rain on canopy-held snow. Drip in this experiment refers to drops of melt water falling from canopy-held snow; it does not include small releases of snow. Throughfall-drip percolate may include some melt from the snowpack during hours when the percolate is passing through the snowpack. During warm, storm-free periods and in the absence of snow in the canopy, all outflow in the forest originates as snowmelt percolate.

Recession flow, which drains slowly from the snowpack, is assigned to the previous outflow event on a prorated basis either as rain, throughfall-drip, or snowmelt percolate. Recession flow near the end of depletion may be a few thousandths of an inch per day; therefore, it may require days to accumulate to 0.01 inch in the catchment tank.

An example of the daily separation of water released from the snowpack at stations 42 and 45 for February 6-12, 1970, is presented in table 2.

Table 2.--*Example of the daily separation of water released from snowpack in the lysimeter for stations 42 and 45, February 6-12, 1970*

February 1970	Maximum air temperature	Precipitation	Presence of snow in canopy	Throughfall-drip percolate	Snowmelt	Total outflow
	°F	Inches		Inches		
			FOREST [STATION 42]			
6	30	0.00	Canopy covered	[1]0.01		0.01
7	33	[2].46	do			.00
8	35	[2].41	do	.05		.05
9	39	[2].08	Canopy partially bare	.1[illegible]		.13
10	40	.00	Canopy bare (observed)	.03	.05	.08
11	41	.00	Canopy bare		.05	.05
12	37	.00	do		.07	.07
Total		.95		.22	.17	.39
			SMALL OPENING [STATION 45]			
				Rain percolate	Snowmelt	
6	31	.08	--			.00
7	35	.00	--			.00
8	37	.00	--			.00
9	42	.00	--			.00
10	42	.00	--	[1].01		.01
11	42	.00	--			.00
12	39	.02	--	.02	.02	.04
Total		.10		.[illegible]	.02	.05

[1]Accumulated recession flow, previous event.
[2]Released as sliding snow and drip from canopy.

EXPERIMENTAL RESULTS

Precipitation and snowpack.--In the upper reaches of the Experimental Forest, wind reduces the efficiency of precipitation (shielded) gages. This effect results in reduced totals, especially in the openings on the south (windward) aspect. Therefore, it is assumed that the catch in the small openings on the north (leeward) aspect come nearer to representing the "true" precipitation. At these sites, seasonal precipitation ranges from 20 to 26 inches (table 3). The amounts were above average at this elevation during the 1968-1969 season and near average during the 1967-1968 and 1969-1970 seasons.

The gages at the forest and small opening sites may register different phases and amounts of precipitation during and after individual storms for reasons not related to the wind factor. For instance, if the trees at the beginning of a storm are bare or nearly bare of snow and the storm is comprised of snow, the gage in the small opening will indicate a much greater catch by a wide margin than the gage in the forest because the overhead canopies are loading and temporarily detaining the snowfall. On the other hand, if it rains when the canopies are snow-loaded from a previous storm, the gage in the forest will invariably show a greater catch than the gage in the small opening because of the addition of sliding snow and drip from the canopy. Occasionally, during storm-free periods, sliding snow and drip will be measured in the gage beneath the canopy; of course, nothing will register in the gage in the small opening (see the precipitation column for February 7-9 in table 2).

Rainfall is interspersed with snowfall during early November which is the period of transition. By December the annual snowpack begins to accumulate, although rainstorms occur infrequently after that time. At the end of the winter season, total rainfall may amount to several inches (table 3). On the north aspect, the snowpack usually attains maximum depth in late March. On the south aspect, the start of the ablation period may occur 40 to 55 days earlier. As expected, the greatest depth of snow (table 3) is in the small openings.

HAUPT, HAROLD F.

1972. The release of water from forest snowpacks during winter, USDA Forest Serv. Res. Pap. INT-114, 17 p., illus.

In the northern Rocky Mountains, in Idaho, data collected during three winters demonstrate why there is always less snow beneath the canopy of a cedar-hemlock forest than in the adjacent small openings. The author presents as evidence the differential release of water, which originates in the canopy as throughfall-drip, thus accounting for part of the deficiency in snow water equivalent beneath the canopy by April 1. Such informative data were made possible by a new instrument designed to collect waterflow from the snowpack.

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Table 3.--*Seasonal precipitation, maximum snow depth, amount of rain, total outflow, and components of outflow (rain percolate, throughfall-drip percolate, and snowmelt percolate) in inches*

Forest stations				Small open stations		
40	42	47		39	45	49
			1967-68			
			Total precipitation	20.26		
24			Maximum snow depth	44		
			Amount of rain	5.10		
18.24			Total outflow	12.79		
			Rain percolate	3.92		
8.34			Throughfall-drip percolate			
9.90			Snowmelt percolate	8.87		
			1968-69			
21.17	22.53		Total precipitation	26.34	23.93	
50	70		Maximum snow depth	78	82	
			Amount of rain	4.56	6.27	
9.44	9.91		Total outflow	7.70	8.56	
			Rain percolate	4.04	5.21	
5.65	6.61		Throughfall-drip percolate			
3.79	3.30		Snowmelt percolate	3.66	3.35	
			1969-70			
17.64	19.67	[1]14.71	Total precipitation	21.58	20.83	16.96
39	45	49	Maximum snow depth	72	71	
			Amount of rain	.84	4.18	.36
6.69	6.23	6.91	Total outflow	4.06	3.97	3.32
			Rain percolate	.71	3.08	1.36
5.82	5.38	5.45	Throughfall-drip percolate			
.87	.85	1.46	Snowmelt percolate	1.35	.89	1.96

[1]November-March, inclusive.
[2]November-January, inclusive.

During 1967-1968 the forest accumulated a very shallow snowpack (24 inches) which did not persist over the usual period because of unseasonable melting in late February and early March. By early March, the lysimeter in the forest became bare several weeks before the lysimeter in the small opening. Actually, the ablation season in 1968 began well before April 1; yet the data are of interest and are included in the report because of the unusual magnitude of melt in midwinter.

Gross release of water from snowpack.--Lysimeter outflow occurred in each of 56 station-months included in the study. Except for brief periods during each November and in March (1968), the outflow drained from an established snowpack. The monthly values range as low as 0.02 inch and as high as 6.72 inches; they also display a diverse range in values among months in each station-year. In contrast, seasonal totals among

stations show a fairly consistent relationship from year to year. All-station outflow was roughly the highest during 1967-1968, intermediate during 1968-1969, and lowest during 1969-1970. A complete tabulation of seasonal outflows is presented for each year, by study, in table 3.

By comparing the lysimeter outflow with precipitation observed during all 3 years at station 39, we find that 63 percent of the precipitation observed during 1967-1968 had drained from the snowpack by April 1; during 1968-1969 the release by April 1 was 29 percent; and during 1969-1970 the release was only 19 percent prior to the spring season.

Sources of water released from snowpack.--Except for a few of the months of study, throughfall-drip percolate in the forest exceeded rain percolate in the small opening. Throughfall-drip percolate reached significant proportions during brief periods of general thaw from December through March. Four weather events in the interval of December 1969 to January 1970 are cited as typical examples of water being released at moderately high rates in the forest and small openings. The individual events plot as rather sharp inflections on the six accumulation curves in figure 5. The extended rises on the three curves for the forested stations include additional water that apparently resulted from melting snow suspended in the trees. (The suspended snow had accumulated in the canopies prior to each general thaw.) All four events in this example are associated with rainfall and a warming trend. In fact, much of the throughfall-drip percolate originates as rain filtering through suspended snow melting in the canopy. At the end of two of the four events, the canopies were completely bare of snow.

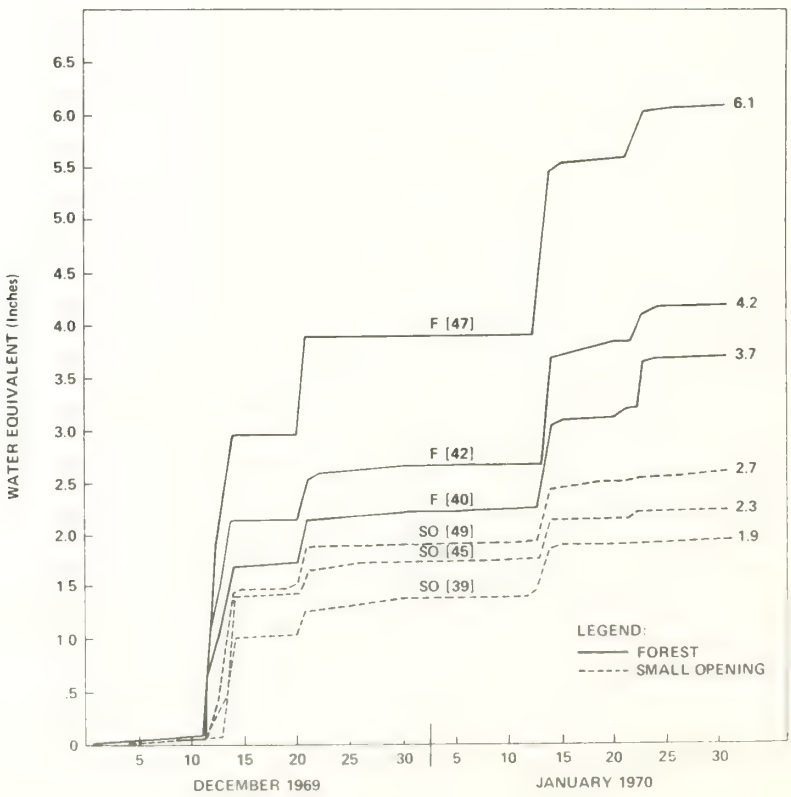


Figure 5.--Accumulated release of water from snowpack for representative period, December 1969-January 1970, at small opening stations SO[39], SO[45], and SO[49], and forest stations F[40], F[42], and F[47]. Number at end of curve represents total release of water in inches for 2-month period.

Table 4.--*Sources of outflow at small opening station 39 and forest station 40 in midwinter, 1968*

Date	Small opening station 39	Sources of outflow	Forest station 40	Sources of outflow	Presence of snow in canopy
	Inch		*Inch*		
February					
11			0.11	M	CB
12			.07	M	CB
13			.05	M	CB (observed)
14					CB
15					CB
16					CB
17					CC[1]
18	0.13	R	.79	T-D	CC[1]
19	.47	R,M	.76	T-D,M	CC-B
20	.42	R,M	.38	T-D,M	CB (observed)
21	.58	R,M	.63	T-D,M	CB
22	.24	R,M	.18	T-D,M	CB
23	.69	R,M	.70	T-D,M	CB
24	.19	M	.18	M	CB
25	.11	M	.20	M	CB
26	.18	M	.27	M	CB
27	.15	M	.35	M	CB(observed)
28	.19	M	.38	M	CB
29	.29	M	.56	M	CB
March					
1	.40	M	.73	M	CB
2	.50	M	.74	M	CB
3	.85	M	[2].83	M	CB
4	.96	M	[2].67	M	CB
5	.73	R,M	[2].39	T-D,M	CB(observed)
6	.15	M	[2].04		CB
7	.04	M	[3]		CB
8	.01	M	[3]		CB
9	.01	M	[3].01	M	CB

LEGEND
R--Rain percolate
T-D--Throughfall-drip percolate
M--Snowmelt percolate
CB--Canopy bare
CC--Canopy covered
CC-B--Canopy partially covered

[1]Storm on February 17-18 precipitated 0.93 inch snow (W.E.) and 0.16 inch rain (sta. 39).
[2]Lysimeter pan partially bare of snow.
[3]Lysimeter pan contained trace of snow.

Of special interest is the amount of throughfall-drip percolate that occurred at station 47 on the south aspect. Water contributed by throughfall and drip at this station is large in comparison with stations on the north aspect (table 3). The contribution for the 2 months exceeded that of station 40 and station 42 by 1.71 inches and 1.31 inches, respectively.

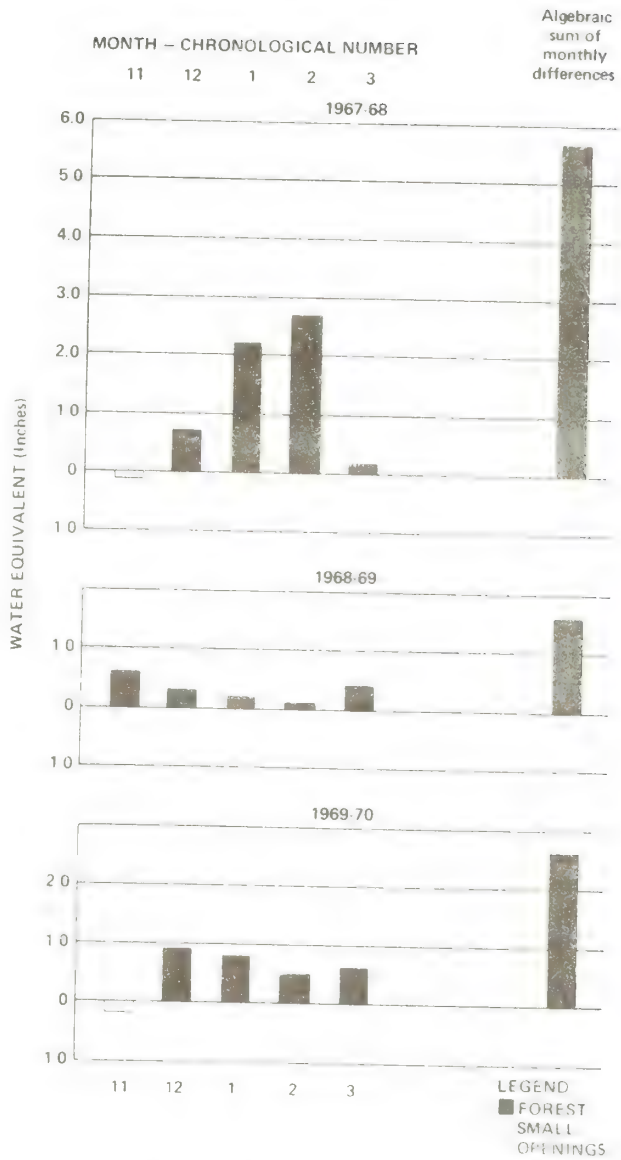
Snowmelt as defined in this study did not occur in every month of the experiment. For instance, during November 1967 melt did not occur because precipitation fell as rain early in the month and drained promptly from the lysimeter pan to catchment tank. By the end of November, snow fell and remained frozen.

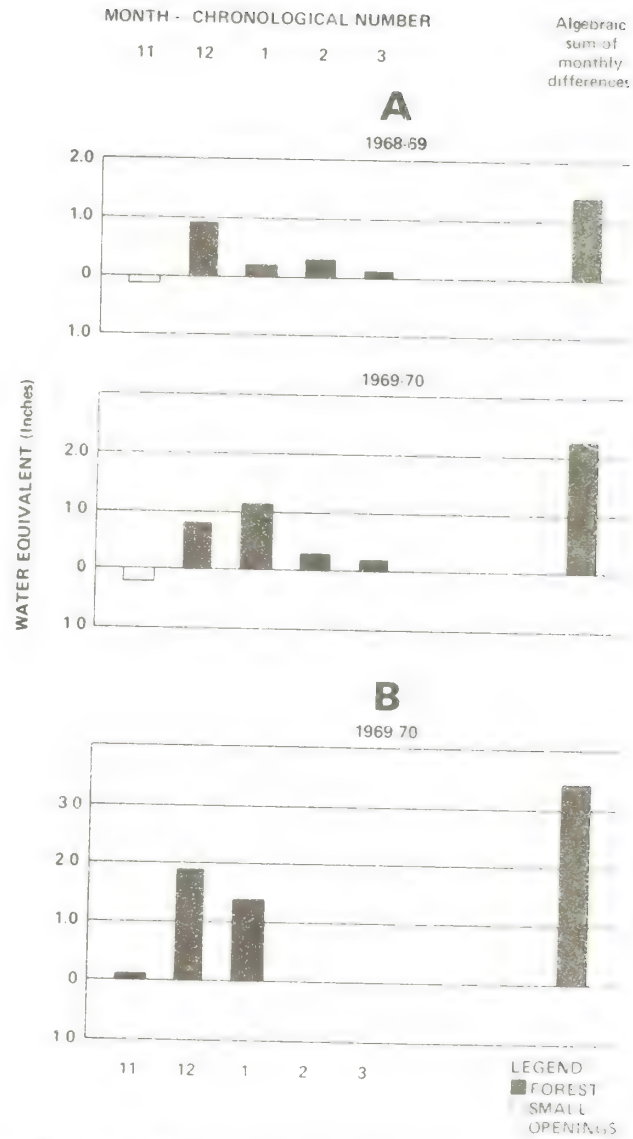
Melt rates from February 24 through March 2, 1968, were abnormally high at the forest station. Prior to February 24, a storm precipitated snow on the 17th; by the next day it turned to rain, continuing to produce rain intermittently through February 23. After clearing (unlike poststorm trends in other winters), the weather remained very mild and clear until after March 2. Snowmelt percolate in the forest for the 8 consecutive days was 70 percent greater than in the small opening (table 4). Throughout the period of clear weather, the canopies were bare of snow; therefore, they did not contribute drip to the snowpack.

From the ablation season (March 26, 1969, until March 31--all clear days), rates of melt were consistently greater in the forest (stations 40 and 42) than in the small openings (stations 39 and 45). There were other isolated periods during winter when rates of melt in the forest were greater (tables 2 and 4). However, the relationship was not consistent; melt in times of cloudy weather generally proved to be slightly greater in the small openings.

Differential release of water from snowpack.--Differential release of outflow is evident between the forest and small openings and between north and south aspects. Mention has already been made of how drip and snowmelt apparently account for most of the variation. A plotting of individual monthly differences as well as the algebraic sum of monthly differences shows the overwhelming effect of the forest in speeding up the release of water (figs. 6 and 7). With exception of four out of six comparisons in November, all remaining comparisons for December, January, February, and March show a difference in favor of the forest condition. Numerically the forest differences for the season range from 1.35 inches in the lowest year to 5.45 inches in the highest year (table 3).

Topographic exposure apparently has an additional effect on seasonal outflow. Based on the months of November, December, and January, outflow from all stations on the south aspect averaged 5.12 inches compared with 3.88 inches on the north aspect. This comparison pertains only to the 1 year (1969-1970) when data were taken on the south aspect.


MONTH – CHRONOLOGICAL NUMBER
11 12 1 2 3
Algebraic sum of monthly differences
1967-68
1968-69
1969-70
WATER EQUIVALENT (Inches)
6.0
5.0
4.0
3.0
2.0
1.0
0
1.0
LEGEND
FOREST
SMALL OPENINGS


MONTH - CHRONOLOGICAL NUMBER
11 12 1 2 3
Algebraic sum of monthly differences
A
1968-69
1969-70
B
1969-70
WATER EQUIVALENT (Inches)
2.0
1.0
0
1.0
3.0
LEGEND
FOREST
SMALL OPENINGS

DISCUSSION

Results of the study show that mature forest cover and topographic exposure greatly influence the release of snow water to the soil mantle. Rainfall prevails at the beginning of winter (early November), and more water is usually available to recharge the soil mantle in small openings than in the forest. Less rainfall reaches the soil in the forest because of canopy interception and retention. With the advent of snowfall (late November) and for the remainder of winter, the situation is reversed; water is released from the snowpack and recharges the soil mantle faster in the forest than in the small openings. Although the results are preliminary, there is some indication that the forest influence is stronger on south than on north aspects.

Throughfall-drip, originating in the canopy, is the major contribution to the greater release of water in the forest. This source of water in turn is strongly dependent upon the detention of snow in the canopy. In the Priest River climate, the deep, thick crowns of mature trees catch and temporarily hold large quantities of snow. This detention capability may relate initially to a favorable air temperature during a snowstorm. The temperature, which seldom goes below 20° F. and generally exceeds 25° F., may ensure high snow density and strong adhesion of snowflakes to the foliage. Rime formation may also contribute to the cohesiveness of snow particles to a minor degree, but we have not assessed this possibility; however, Berndt and Fowler (1) reported that rime formed concomitantly with snowfall. Their work was conducted west of Priest River Experimental Forest at an elevation of 6,100 feet in eastern Washington.

Although the temperature during a storm may contribute to detention of snow, tree-branching characteristics very likely play an important role. In observing sapling trees at a lower elevation (2,500 feet), we have found that the bulk of the snow readily slides off the narrow, limber branches in a matter of hours after each storm (8). The stiffer branches and wider foliage of mature trees at a higher elevation (4,300 feet) provide a more sturdy "platform" for holding snow loads.

Comparison of precipitation records in the forest and small openings as well as close observations on weekly trips to the study site indicate that snow tends to persist on the mature trees--sometimes for several weeks. Unlike the climatic conditions in Colorado (5), very little snow blows off the canopy and redeposits in the small openings. When snow does dislodge, usually it falls to the forest floor as massive wet clumps.

This lengthy persistence of snow in the canopy enhances the opportunity that the snow will be acted upon either by subsequent storms or by clear weather conducive to evaporation or melting. It is not uncommon for a new storm following in the wake of an old storm to be accompanied by above-freezing temperatures and thus produce rain. The rainy, thawing condition rapidly changes the physical properties of canopy-held snow and drip begins to fall within a short time. Snow clumps heavy with water slide out of the trees, but much of the intercepted snow holds fast to branches and foliage until dissipated by melting. (Our field crews often experience considerable discomfort when working under the canopy on a "heavy-drip" day.)

Noteworthy information derived from the study has been the high intensity and volume of outflow (primarily throughfall-drip percolate) recorded in the forest usually on the beginning day of a rainy, thawing condition. This volume of outflow often exceeds the outflow (primarily rain percolate) in the small openings by a wide margin. By inference, the excess outflow is attributed to drip from snow held over in the canopy from a previous snowstorm.

This poses the question as to whether the entire contribution of excess outflow has its origin as drip from snow in the canopy. There are two other possible sources--differential input by rainfall and differential melt in the snowpack. There is no scientific evidence to show that rainfall incident on the canopy is substantially greater than that which falls in the small openings. Most investigators claim that the input to the forest canopy may in fact be less than in the openings (7). Indeed, if this is the case, then by our analysis technique the outflow assigned to drip is a conservative estimate.

There is the theoretical chance that more heat energy from the warm air masses is absorbed by the crowns and transmitted to the snowpack by convection and radiation. We discount this possibility because, during periods when canopies are bare of snow and warm air masses are passing in absence of rain (i.e., warm winds or Chinook conditions), the lysimeter charts in the forest exhibit no sudden surge of snowmelt percolate. In actuality, when these conditions prevail the sky is usually heavily overcast and the melt rate is comparable or slightly faster in the small openings.

The first-day outflow of throughfall-drip in the forest often percolates down through the snowpack at a rapid rate. Possibly there are extended periods during winter when the snowpack in the forest maintains an isothermal condition concomitant with complete or near-complete recharge of liquid water. As a consequence, the snowpack responds rapidly to the smallest input of throughfall-drip or heat energy. This is substantiated by the brief lag time before outflow appears in the lysimeter.

In the deeper snowpack in the small openings, conditions are different. The initial lag time is usually greater, especially after an extended period of clear, cold weather and, therefore, responses to rain and heat energy are correspondingly slower--probably because of the freezing of rain or refreezing of surface melt deeper in the pack.

Unusually warm, sunny weather, such as occurred in midwinter 1968, causes the snowpack on the north aspect to melt faster in the forest than in the small openings. This is attributed to a difference in the net energy balance between the forest and small openings. The fact that the winter sun traverses a low arc on the southern horizon apparently is not a disadvantage to a dense forest stand on a north slope. The tall, projecting crowns, which expose a dark green mass with some surfaces actually perpendicular to the sun's rays, readily absorb solar radiation and in turn reradiate considerable amounts of thermal energy to the snowpack. In contrast, the snowpack in the small openings presents a highly reflective surface which slopes to the north and away from the sun's rays, thus reducing the amount of absorbed radiation. This explanation, although conjectural, seems plausible in light of radiation measurements taken by Hornbeck (6) in an eastern forest. He reports that on clear days in February a forest (hardwood) site absorbed 2.6 times more downward solar radiation than a clearcut site. He goes on to state:

> ...That on clearer days sensible heating of the snow cover and subsequent melting may be more rapid for the forest site, provided little or no slash protrudes above the snow at the clearcut site. The above conditions could delay the advance in snowmelt runoff often associated with clearcutting... .

The lysimeter results at Priest River support Hornbeck's speculation as it applies to small openings on the north slope of a western coniferous forest.

Conclusions

The release of water from the snowpack in winter is a very important geophysical process, the ramifications of which could apply to any forest conditions and climates similar to those in Priest River. The significant happening in this process is that the volume of outflow beneath the canopy exceeds that in small openings, resulting in less snow water equivalent in the forest by April 1. During a typical winter the evidence suggests that most of the difference in outflow originates in the canopy where intercepted snow is converted to drip which in turn percolates through the snowpack and hence becomes a net loss to snow storage.

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A MATHEMATICAL MODEL FOR PREDICTING FIRE SPREAD IN WILDLAND FUELS

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A MATHEMATICAL MODEL FOR PREDICTING FIRE SPREAD IN WILDLAND FUELS

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U.S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

PREFACE

Forest managers as well as those engaged in research involving fires in forests, brush fields, and grasslands need a consistent method for predicting fire spread and intensity in these fuels. The availability of the mathematical model of fire spread presented in this paper offers for the first time a method for making quantitative evaluations of both rate of spread and fire intensity in fuels that qualify for the assumptions made on the model. Fuel and weather parameters *measurable in the field* are featured as inputs to the model. It is recognized that this model of the steady-state fire condition is only a beginning in modeling wildland fires, but the initial applications to the National Fire-Danger Rating System and to fuel appraisal illustrate its wide applicability.

The introduction of this model will permit the use of systems analysis techniques to be applied to land management problems. As a result, a new dimension is offered to land managers for appraising the consequences of *proposed* programs. Questions can be answered such as: What is the resultant fuel hazard when thinning is done in overstocked areas? Can logging practices be modified to reduce the potential fire hazard of the fuels they produce? How much slash should be left on the ground to produce the desired site treatment for the next crop of trees? How long after cutting can a successful burn still be achieved? What is the hazard buildup in chaparral brush fields of the Los Angeles Basin in years subsequent to the last burn?

Systems analysis can be applied not only to these broader aspects of vegetative manipulation activities, but also to traditional activities, such as presuppression planning and prescribed burning. As we learn more about the growth and decay patterns of our fuels, the long-range consequences of management policy can be examined and appraised on a quantitative basis. Decisions will be more often in line with the desired outcome when the alternatives to proposed practices can be compared and evaluated *before* a stick of wood is cut.

This mathematical model has been developed for predicting rate of spread and intensity in a continuous stratum of fuel that is contiguous to the ground. The initial growth of a forest fire occurs in the surface fuels (fuels that are supported within 6 feet or less of the ground). Under favorable

burning conditions, if sufficient heat is generated, the fire can grow vertically into the treetops causing a crown fire to develop. The nature and mechanisms of heat transfer in a crown fire are considerably different than those for a ground fire. Therefore, the model developed in this paper is not applicable to crown fires. An exception can be made for brush fields. Brush, such as chamise, is characterized by many stems and foliage that are reasonably contiguous to the ground, making it suitable for modeling as a ground fire.

Contributions to the spread of the fire by firebrands have not been included. At first this may seem to be a serious limitation to the model because everyone who has been on a large fire (most investigators go to large fires, the fires not presently being modeled) knows the importance of spotting. However, seeing firebrands in the air and landing ahead of the fire front does not mean that they are effective in advancing the fire. Berlad (1970) has shown that not all firebrands have a significant effect in spreading a fire. To be significant, firebrands must release sufficient heat when they land to ignite the adjacent fuels, and they must do so before the fire would have overrun the descent point as a result of conventional heat transfer mechanisms.

Furthermore, the model has been designed to simulate a fire that has stabilized into a quasi-steady spread condition. Most fires begin from a single source and spread outward, growing in size and assuming an elliptical shape with the major axis in the direction most favorable to spread. When the fire is large enough so that the spread of any portion is independent of influences caused by the opposite side, it can be assumed to have stabilized into a line fire. A line fire behaves like a reaction wave with progress that is steady over time in uniform fuels.

All input parameters can be determined from knowledge of the characteristics of fuels in the field. This does not imply that all the parameters of fuels and environment are readily available or can easily be measured. It does, however, delineate what parameters should be cataloged and eliminates those that are not needed. A convenient method of cataloging input parameters is through the concept of fuel models tailored to the vegetation patterns found in the field. The companion fuel models are thus a set of input parameters that describe the inherited characteristics that have been found in certain fuel types in the past. The environmental parameters of wind, slope, and expected moisture changes may be superimposed on the fuel models. This fuel model concept has already been incorporated into the National Fire-Danger Rating System (Deeming and others 1972).

The mathematical model produces quantitative values of spread and intensity that should be regarded as appraised or mean values for the given fuel and environmental conditions. The National Fire-Danger Rating System, however, will display the values on a relative scale in the form of indexes. The indexes developed from this mathematical model can be designed to predict conditions during which severe fire phenomena develop, even though the model does not include mass fire effects.

Concurrently, studies designed to confirm portions of the model through field tests have been conducted and are reported by J. K. Brown (1972).

THE AUTHOR

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ABSTRACT

The development of a mathematical model for predicting rate of fire spread and intensity applicable to a wide range of wildland fuels is presented from the conceptual stage through evaluation and demonstration of results to hypothetical fuel models. The model was developed for and is now being used as a basis for appraising fire spread and intensity in the National Fire-Danger Rating System. The initial work was done using fuel arrays composed of uniform size particles. Three fuel sizes were tested over a wide range of bulk densities. These were 0.026-inch-square cut excelsior, 1/4-inch sticks, and 1/2-inch sticks. The problem of mixed fuel sizes was then resolved by weighting the various particle sizes that compose actual fuel arrays by either surface area or loading, depending upon the feature of the fire being predicted.

The model is complete in the sense that no prior knowledge of a fuel's *burning* characteristics is required. All that is necessary are inputs describing the physical and chemical makeup of the fuel and the environmental conditions in which it is expected to burn. Inputs include fuel loading, fuel depth, fuel particle surface-area-to-volume ratio, fuel particle heat content, fuel particle moisture and mineral content, and the moisture content at which extinction can be expected. Environmental inputs are mean wind velocity and slope of terrain. For heterogeneous mixtures, the fuel properties are entered for each particle size. The model as originally conceived was for dead fuels in a uniform stratum contiguous to the ground, such as litter or grass. It has been found to be useful, however, for fuels ranging from pine needle litter to heavy logging slash and for California brush fields.

The concept of *fuel models* is introduced, wherein parameters of wildland fuels necessary for inputs to the model are categorized and tabulated. These are then used to predict fire spread and intensity; this eliminates the necessity for repeatedly measuring such parameters. The conceptual approach recognizes that fuels have inherent characteristics that are repeatable.

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HOW FIRE SPREADS

Early work in fire spread research conducted by the USDA Forest Service was primarily aimed at developing relationships between burning conditions and obvious variables that would aid forest managers to cope with fire problems. Such variables as fuel moisture, fuel loading, wind velocity, relative humidity, slope, and solar aspect were all recognized as producing important effects on fire. These effects were studied and correlated to some form of fire behavior. The work was primarily done outdoors and some very good results were obtained, considering the complexities of the problem and the variability of weather, particularly wind. Much of the present day fire-danger rating, fuel classification, and other uses of fire research are based on this pioneering work.

W. R. Fons (1946) was the first to attempt to describe fire spread using a mathematical model. Fons focused his attention on the head of the fire where the fine fuels carry the fire and where there is ample oxygen to support combustion. He pointed out that sufficient heat is needed to bring the adjoining fuel to ignition temperature at the fire front. Therefore, Fons reasoned that fire spread in a fuel bed can be visualized as proceeding by a series of successive ignitions and that its rate is controlled primarily by the ignition time and the distance between particles.

Fon's early ideas have been confirmed by recent work in flame spread theory. Tarifa and Torralbo (1967) state that:

> Heating of the fuel ahead of the flame as it progresses is the first and most essential process of the flame propagation mechanism. Therefore, it is very important to know the flame propagation mechanism from flame to fuel and to study the time consumed for the heating process since it may control propagation speed in many cases. Nevertheless, there is little information on these problems.

McAlevy and others[1] theorized that:

> The phenomena of flame spreading over an igniting propellant surface is viewed herein as one of continuous, diffusive, gas-phase ignition; thus, the flame spreading phenomena is linked inextricably to the ignition phenomena.

[1]Robert F. McAlevy, III, Richard S. Magee, and John A. Wrubel. Flame spreading at elevated pressures over the surface of igniting solid propellants in oxygen/inert environments. (Paper presented at spring meeting of Western States Sect. Combust. Inst., 1967.)

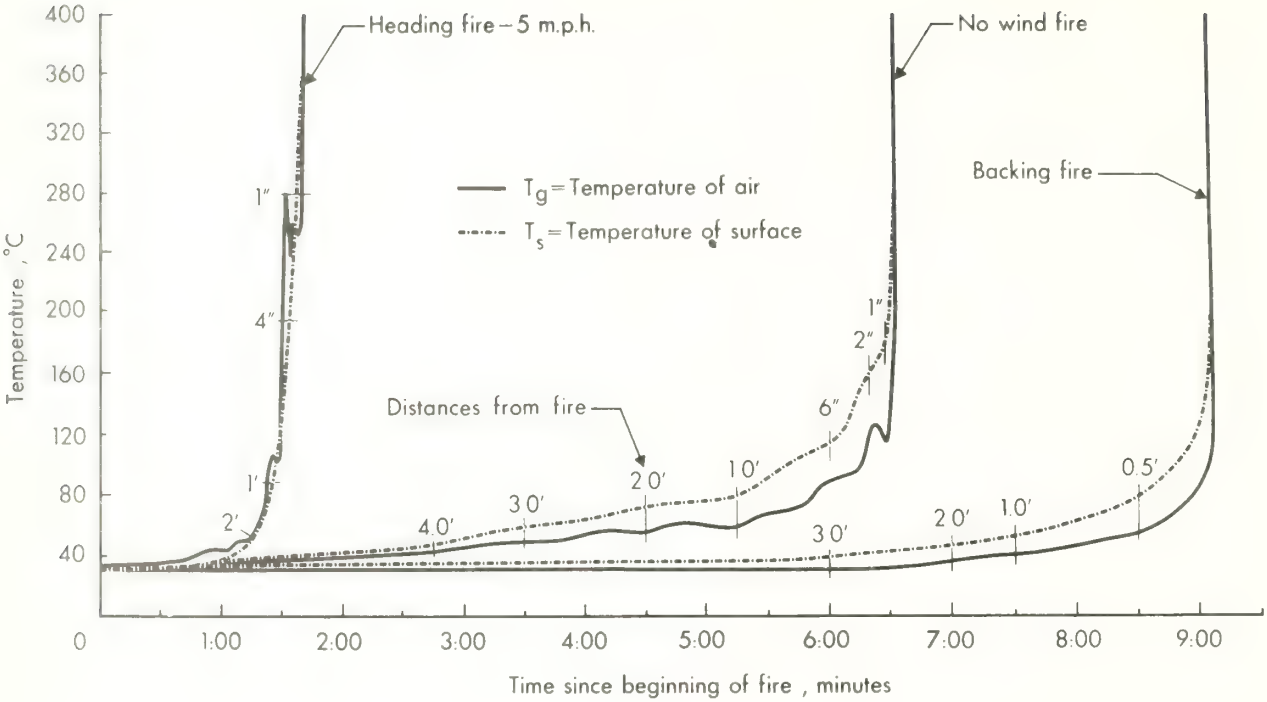


Figure 1.--Fuel temperature history prior to ignition for heading, no-wind, and backing fires.

Considering fire as a series of ignitions helps in breaking down the problem for analysis. Heat is supplied from the fire to the potential fuel, the surface is dehydrated, and further heating raises the surface temperature until the fuel begins to pyrolyze and release combustible gases. When the gas evolution rate from the potential fuel is sufficient to support combustion, the gas is ignited by the flame and the fire advances to a new position. Finally, a constant rate of spread is achieved; this is called the "quasi-steady state" wherein the fire advances at a rate that is the average of all the elemental rates.

This process is illustrated in figure 1, which is based on a laboratory test in which we monitored the surface temperature of a fine fuel element and the air adjacent to it ahead of an advancing fire. In the no-wind fire and backing fires, the fuel temperature rose slowly until the fire was within 1 or 2 inches of the fuel element where it suddenly rose to ignition. During the *preheating phase*, the fuel temperature exceeded the air temperature; this indicates that convective heating or direct flame contact does not occur until the fire front reaches the particle. Consequently, radiation must have accounted for the energy imparted to the fuel elements on the upper surface while simultaneously the particle was being cooled by convective indrafts. This does not occur in the heading, or wind-driven fire, in which the temperature of the fuel rose steeply even when the fire was 2 feet from the thermocouple that had been inserted in the particle. During the rise to ignition, the air temperature was higher than the fuel surface temperature; this shows that convective heating can be present in addition to radiation. Such temperature histories indicate that basic differences exist in the mechanisms that bring fuels to ignition. These basic differences provided us with a method for characterizing fires and developing similar methods for mathematical modeling.

CONCEPTION OF MATHEMATICAL MODEL

The model was developed from a strong theoretical base to make its application as wide as possible. This base was supplied by Frandsen (1971) who applied the conservation of energy principle to a unit volume of fuel ahead of an advancing fire in a homogeneous fuel bed. His analysis led to the following:

$$R = \frac{\int_{0}^{\infty} \left(\frac{\partial I}{\partial z}\right)}{\rho_{be} Q_{ig}}$$

where:

R = quasi-steady rate of spread, ft./min.

I_{xig} = horizontal heat flux absorbed by a unit volume of fuel at the time of ignition, B.t.u./ft.^{2}-min.

ρ_{be} = effective bulk density (the amount of fuel per unit volume of the fuel bed raised to ignition ahead of the advancing fire), lb./ft.^{3}

Q_{ig} = heat required for ignition, B.t.u./lb.

$\left(\frac{\partial I}{\partial z}\right)$ = the gradient of the vertical intensity, evaluated at a point at a depth, z, in the fuel bed, B.t.u./ft.^{2}-min.

The short vertical and horizontal coordinates are z and x, respectively.

Intensity, I, and heat content, Q, have the same value ($I = Q$) at the surface ($z = 0$) and at a depth, z, from the surface equal to the depth of the unit volume. The unit volume ignites at the interface.

The gradient of the vertical intensity, $\left(\frac{\partial I}{\partial z}\right)$, evaluated at the surface, is a ratio between the heat flux received from the source in the numerator and the heat required to raise the unit volume to ignition in the denominator. The numerator contains heat flux terms for which the mechanisms of heat transfer are not known; consequently, it was necessary to examine each term and determine experimental and analytical methods of evaluation. This required the definition of new terms that ultimately provided an approximate solution to equation (1).

Heat Required for Ignition

The heat required for ignition is dependent upon (a) ignition temperature, (b) moisture content of the fuel, and (c) amount of fuel involved in the ignition process.

The energy per unit mass required for ignition is the heat of preignition, Q_{ig}:

$$Q_{ig} = f(M_f, T_{ig}), \text{ B.t.u./lb.} \tag{2}$$

where:

M_f = ratio of fuel moisture to ovendry weight

T_{ig} = ignition temperature.

The amount of fuel involved in the ignition process is the effective bulk density, ρ_{be}. To aid interpretation and analysis, an effective heating number is defined as the ratio of the effective bulk density to the actual bulk density.

$$\varepsilon \equiv \frac{\rho_{be}}{\rho_b} . \tag{3}$$

The effective heating number is a dimensionless number that will be near unity for fine fuels and decrease toward zero as fuel size increases. Therefore,

$$\rho_{be} = f(\text{bulk density, fuel size}) . \tag{4}$$

Propagating Flux

The propagating flux is the numerator of the RHS (right-hand side) of equation (1) and has the units of heat per unit area, per unit time. The propagating flux is represented by I_p:

$$I_p = I_{xig} + \int_{-\infty}^{0} \left(\frac{\partial I_z}{\partial z}\right)_{z_c} dx, \text{ B.t.u./ft.}^2\text{-min.} \tag{5}$$

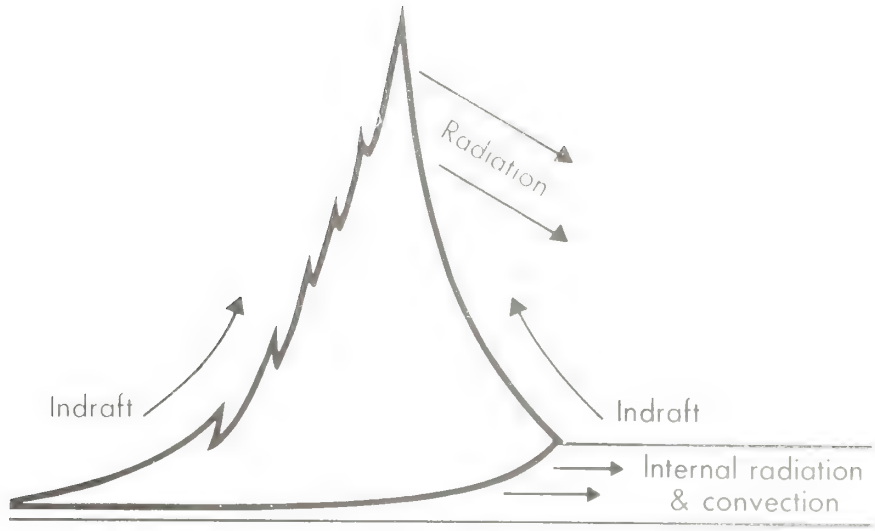
The propagating flux is composed of two terms, the horizontal flux and the gradient of the vertical flux integrated from minus infinity to the fire front. These fluxes can be characterized as shown in figures 2, 3, and 4. The figures indicate that the vertical flux is more significant during wind-driven and upslope fires because the flame tilts over the potential fuel, thereby increasing radiation, but more significantly causing direct flame contact and convective heat transfer to the potential fuel.

We will assume the vertical flux is small for no-wind fires and let $I_p = (I_p)_o$. In the model, $(I_p)_o$ is the basic heat flux component to which all additional effects of wind and slope are related.

When we substitute equations (3) and (5) into equation (1) and let $I_p = (I_p)_o$ and $R = R_o$ for the no-wind case, then

$$(I_p)_o = R_o \rho_b \varepsilon Q_{ig}, \text{ B.t.u./ft.}^2\text{-min.} \tag{6}$$

Figure 2.--Schematic of no-wind fire.



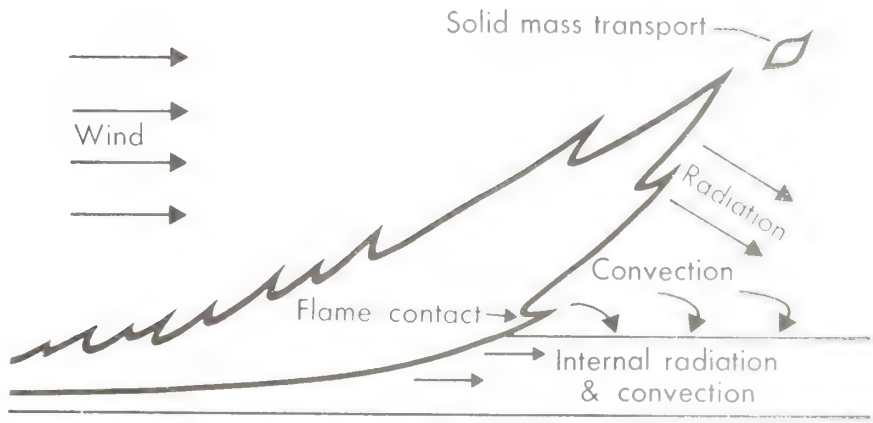


Figure 3.--Schematic of wind-driven fire.

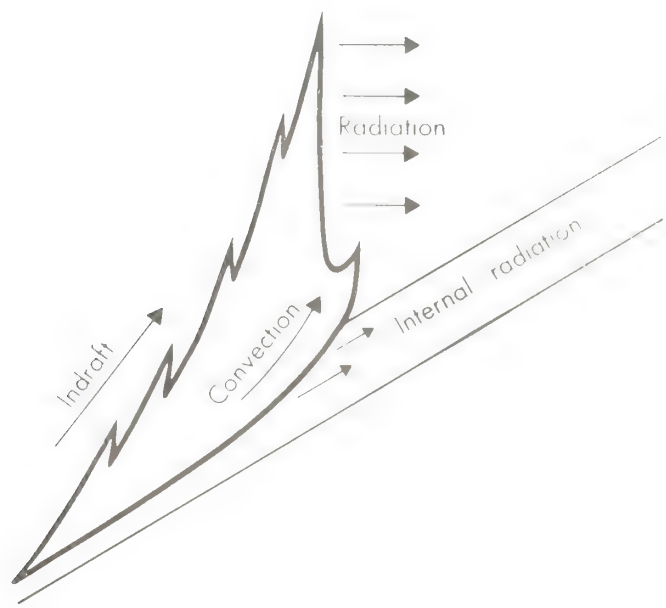


Figure 4.--Schematic of upslope fire.

Equation (6) permits $(I_p)_o$ to be evaluated from experiments with spreading fires in the no-wind condition by measuring R_o over a wide range of fuel conditions. Note that the propagating flux occurs at the front of the fire; therefore $(I_p)_o$ is expected to be closely related to the fire intensity of the front:

Reaction Intensity

The energy release rate of the fire front is produced by burning gases released from the organic matter in the fuels. Therefore, the rate of change of this organic matter from a solid to a gas is a good approximation of the subsequent heat release rate of the fire. The heat release rate per unit area of the front is called the reaction intensity and is defined as:

$$I_R = -\frac{dw}{dt} h, \text{ B.t.u./ft.}^2\text{-min.} \tag{7}$$

where:

$\frac{dw}{dt}$ = mass loss rate per unit area in the fire front, lb./ft.^{2}-min.

h = heat content of fuel, B.t.u./lb.

The reaction intensity is a function of such fuel parameters as the particle size, bulk density, moisture, and chemical composition.

The reaction intensity is the source of the no-wind propagating flux, $(I_p)_o$. An important concept upon which the model is based that $(I_p)_o$ and I_R can be evaluated independently and correlated. Knowing the correlation, $(I_p)_o$ can be determined from the reaction intensity, which is in turn dependent on fuel parameters obtained from the fuel bed complex.

$$(I_p)_o = f(I_R). \tag{8}$$

If this concept is kept in mind, it will aid in understanding the development of the model.

Effect of Wind and Slope

Wind and slope change the propagating heat flux by exposing the potential fuel to additional convective and radiant heat (figs. 3 and 4).

Let ϕ_W and ϕ_S represent the additional propagating flux produced by wind and slope. They are dimensionless coefficients that are functions of wind, slope, and fuel parameters. They must be evaluated from experimental data. The total propagating flux is represented by the expression,

$$I_p = (I_p)_o (1+\phi_W+\phi_S). \tag{9}$$

Approximate Rate of Spread Equation

Inserting the approximate relationships, equation (1) becomes:

$$R = \frac{(I_p)_o (1+\phi_W+\phi_S)}{\rho_b \varepsilon Q_{ig}}. \tag{10}$$

EVALUATION OF PARAMETERS, NO-WIND, OR SLOPE

The conceived functional relationships necessary for evaluating equation (1) are divided and considered first as those forming a heat sink, and second as those serving as a heat source.

Heat Sink

The heat of preignition and the effective bulk density are the two terms that had to be evaluated before the propagating flux could be computed. Q_{ig} was evaluated analytically for cellulosic fuels by considering the change in specific heat from ambient to ignition temperature and the latent heat of vaporization of the moisture.

$$Q_{ig} = C_{pd} \Delta T_{ig} + M_f (C_{pw} \Delta T_B + V) \quad (11)$$

where:

C_{pd} = specific heat of dry wood

ΔT_{ig} = temperature range to ignition

M_f = fuel moisture, lb. water/lb. dry wood

C_{pw} = specific heat of water

ΔT_B = temperature range to boiling

V = latent heat of vaporization.

Details of the calculation are given by Frandsen.[2] The temperature to ignition is assumed to range from 20° to 320° C. and boiling temperature to be at 100° C., then equation (11) becomes:

$$Q_{ig} = 250 + 1{,}116\ M_f, \text{ B.t.u./lb.} \quad (12)$$

[2] W. H. Frandsen. The effective heating of fuel particles ahead of a spreading fire. USDA Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah (in preparation).

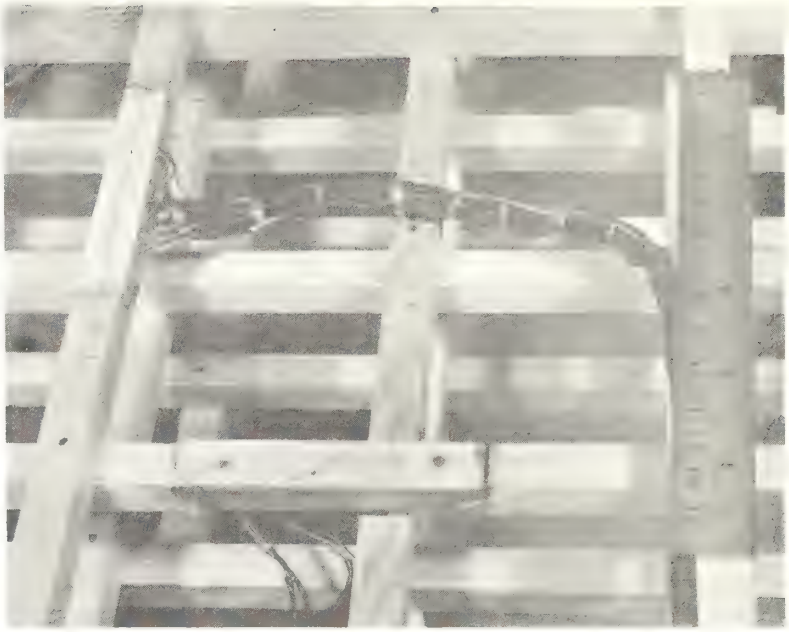


Figure 5.--Instrumentation for determining the effective bulk density.

Moisture is the primary independent variable in the evaluation of Q_{ig}; however, it is recognized that other parameters should eventually be included in this evaluation: heating rate, inorganic impurities, and nonpyrolytic volatiles.

Effective Bulk Density

To evaluate the effective bulk density (ρ_{be}), we needed to determine the efficiency of heating as a function of particle size. This was evaluated by placing thermocouples within sections of two sticks that were located on the upper surface 3 feet from one end of standard wood cribs.[3] The instrumented sections were oriented in both the longitudinal and lateral directions (fig. 5). The temperature distribution within the sticks was analyzed to determine the amount of heat absorbed by the sticks up to the time of ignition.

Results of the analysis are shown in figure 6. An exponential fit to the data is:

$$\varepsilon = \exp(-138/\sigma) \qquad (14)$$

where:

σ = particle surface-area-to-volume ratio, $ft.^{-1}$

If we take unity as being 100-percent heating for a hypothetical zero-thickness fuel, figure 6 shows that 22 percent of the 1/2-inch stick and 50 percent of the 1/4-inch stick must be heated to ignition; it also predicts that 92.8 percent of the excelsior is heated. This agreed with our original assumption of 100 percent for fine fuels.

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[3]Frandsen, ibid.

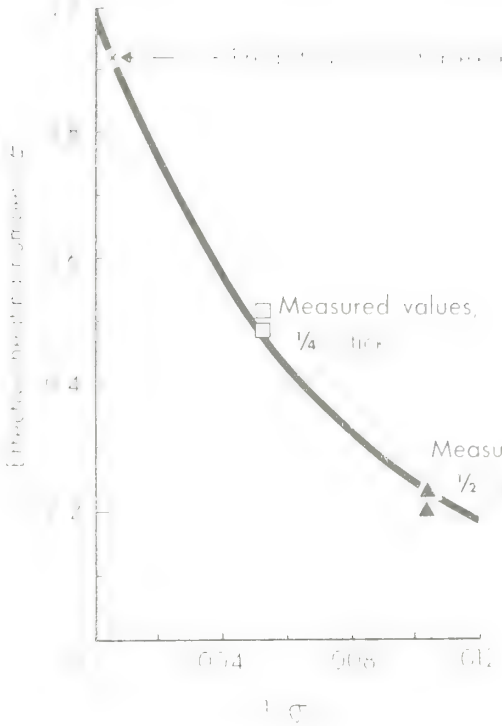


Figure 6.--Effective heating number versus 1/σ. σ is the surface-area-to-volume ratio; is a measure of the fraction of the potential fuel that must be raised to ignition.

Heat Source

Reaction Intensity

that evolved by deriving fire intensity from the weight loss data.[4] The evaluation was made from a series of experiments utilizing an instrument system that recorded the weight of a portion of the fuel bed during fire spread.

Equation (7) can be rearranged to express reaction intensity in the following manner:

where:

dx = R, the quasi-steady rate of spread.
dt

Therefore,

[4]W. H. Frandsen and R. C. Rothermel. Measuring the energy release rate of a spreading fire. USDA Forest Serv., Intermountain Forest and Range Exp. Station, Ogden, Utah (in preparation).

This gives

$$I_R D = Rh(w_n - w_r). \tag{18}$$

where:

D = reaction zone depth (front to rear), ft.

w_n = net initial fuel loading, lb./ft.^{2}

w_r = residue loading immediately after passage of the reaction zone, lb./ft.^{2}

The net initial fuel loading was corrected for the presence of noncombustibles, water, and minerals.

The time taken for the fire front to travel a distance equivalent to the depth of one reaction zone is the reaction time τ_R.

$$\tau_R = \frac{D}{R}. \tag{19}$$

Substituting the reaction time into equation (18) gives

$$I_R = \frac{h(w_n - w_r)}{\tau_R}. \tag{20}$$

We now define a maximum reaction intensity where there is no loading residue left after the reaction zone is passed and where the reaction time remains unchanged. This maximum reaction intensity is represented by

$$I_{Rmax} = \frac{hw_n}{\tau_R}. \tag{21}$$

The reaction zone efficiency is then defined as

$$\eta_s = \frac{I_R}{I_{Rmax}} = \frac{(w_n - w_r)}{w_n}. \tag{22}$$

Replacing $(w_n - w_r)$ in equation (20), we have I_R in terms of measurable fuel and fire parameters.

$$I_R = \frac{w_n h \eta_s}{\tau_R}. \tag{23}$$

The net fuel loading necessary for equation (23) can be obtained from equation (24).

$$w_n = \frac{w_o}{1+S_T} \tag{24}$$

where:

w_o = ovendry fuel loading, lb./ft.^{2}

S_T = fuel mineral content, $\frac{\text{lb. minerals}}{\text{lb. dry fuel}}$.

The reaction velocity is a dynamic variable that indicates the completeness and rate of fuel consumption. Therefore, it represents the dynamic character of the fire and is the key to successful development of the model.

The reaction velocity is defined as the ratio of the reaction zone efficiency to the reaction time,

$$\Gamma \equiv \frac{\eta}{\tau_R} \quad \text{reaction velocity, min.}^{-1}. \tag{25}$$

Four fuel parameters are considered to have a major effect on the reaction velocity--moisture content, mineral content, particle size, and fuel bed bulk density.

Fuel moisture and mineral content are introduced through two damping coefficients that operate on the potential reaction velocity; the latter is the reaction velocity that would exist if the fuel were free of moisture and contained minerals at the same concentration as alpha cellulose. The presence of moisture or minerals reduces the reaction velocity below its potential value.

Let:

Γ' = potential reaction velocity, min.$^{-1}$

η_M = moisture damping coefficient having values ranging from 1 to 0, dimensionless.

η_s = mineral damping coefficient having values ranging from 1 to 0, dimensionless.

Then:

Substituting equations (25) and (26) into equation (23) produces the final expression for reaction intensity.

The reaction velocity and the moisture and mineral damping coefficients must be evaluated by experimentation.

The moisture damping coefficient is defined as

Anderson (1969) tested identical fuel beds of ponderosa pine needles over a wide moisture range. The ratio $I_R/I_{R_{max}}$ or η_M, as plotted in figure 7, was obtained from his data.

The abscissa in figure 7 is the ratio of M_f, the fuel moisture, to M_x, the moisture of extinction. M_x is the moisture content of the fuel at which the fire will not spread. For litter fuels of ponderosa pine needles, $M_x \approx 0.30$; for other dead fuels,

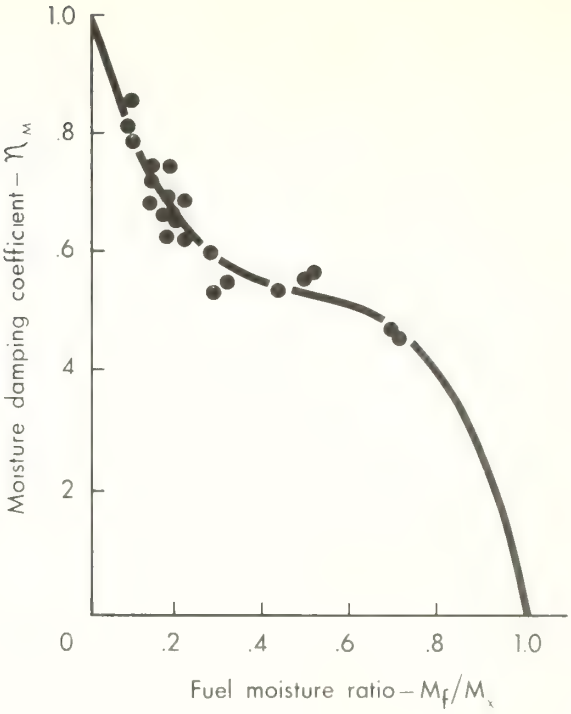


Figure 7.--Determination of moisture damping coefficient from ponderosa pine needle fuel beds.

it may vary between 0.10 and 0.40.[5] Recent field experiments in logging slash (Brown 1972) indicate that M_x may be between 0.10 and 0.15 for logging slash, which is more porous than litter.

The equation for the curve in figure 7 is

$$\eta_M = 1 - 2.59 \frac{M_f}{M_x} + 5.11\left(\frac{M_f}{M_x}\right)^2 - 3.52\left(\frac{M_f}{M_x}\right)^3 . \qquad (29)$$

The moisture damping coefficient accounts for the decrease in intensity caused by the combustion of fuels that initially contained moisture. The exact effect of the moisture has not been adequately explained in terms of reaction kinetics.

Q_{ig} is included implicitly in the development of η_M. If further studies of Q_{ig} reveal it to be nonlinear, then the curve form of η_M will change.

Mineral Damping Coefficient

The mineral damping coefficient was evaluated from thermogravimetric analysis (TGA) data of natural fuels by Philpot (1968). In this study, it was assumed that the ratio of the normalized decomposition rate would be the same as the normalized reaction intensity. The maximum decomposition rate used for normalization was at a mineral content of 0.0001, a value that was assumed to be the lowest fractional mineral content for natural fuels. Philpot found that silica did not affect the decomposition rate. Therefore, the silica-free ash content was taken as the independent parameter. The data are shown in figure 8. The equation for the curve in figure 8 is

$$\eta_S = 0.174(S_e)^{-.19} \qquad (30)$$

where: S_e = effective mineral content (silica free).

[5]To avoid confusion in equation development, the moisture and mineral values are expressed as a ratio rather than a percent.

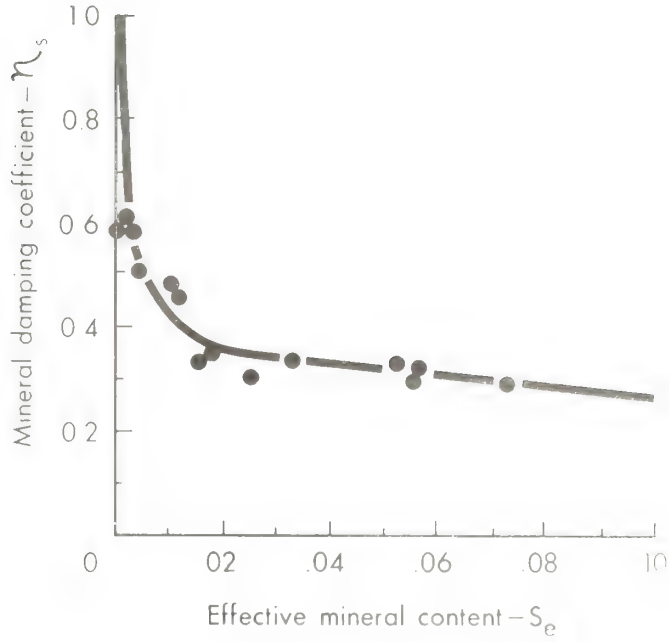


Figure 8.--Mineral damping coefficient of natural fuels, derived from the work of Philpot (1968).

Physical Fuel Parameters

Two variables remain that had to be considered in evaluating the reaction intensity--fuel bed compactness and fuel particle size. Both are known to have significant effects upon combustibility, but to date, integrated research has not been conducted to separate and quantify the effects of these variables on the dynamic character of fire.

It is hypothesized that low values of fire intensity and rate of spread occur at the two extremes of compactness (loose and dense). In dense beds, this can be attributed to low air-to-fuel ratio and to poor penetration of the heat beyond the upper surface of the fuel array. In loose beds (at the other extreme), low intensity and poor spread are attributed to heat transfer losses between particles and to lack of fuel. Between these two extremes, therefore, there must be an optimum arrangement of fuel that will produce the best balance of air, fuel, and heat transfer for both maximum fire intensity and reaction velocity. It is not expected that the optimum arrangement will be the same for different size fuel particles.

The compactness of the fuel bed is quantified by the packing ratio, which is defined as the fraction of the fuel array volume that is occupied by fuel. The packing ratio can be easily calculated by evaluating the ratio of the fuel array bulk density to the fuel particle density,

$$\beta = \frac{\rho_b}{\rho_p} \qquad (31)$$

where:

β = packing ratio, dimensionless

ρ_b = fuel array bulk density, lb./ft.^{3}

ρ_p = fuel particle density, lb./ft.^{3}.

The surface-area-to-volume ratio is used to quantify the fuel particle size.

Let σ = the fuel particle surface-area-to-volume ratio. For fuels that are long with respect to their thickness,

$$\sigma = \frac{4}{d}, \text{ ft.}^{-1} \tag{32}$$

where:

d = diameter of circular particles or edge length of square particles, ft.

The packing ratio of the fuel array, β, and the surface-area-to-volume ratio of the fuel particle, σ, are the primary independent variables used throughout the remainder of the paper for evaluating correlation equations.

Experimental Design

To evaluate the reaction velocity, a weighing platform was constructed as part of the fuel support surface for the experimental fuel beds. This weighing platform, which was 18 inches square, was supported by four load cells, which were protected from the heat by a series of baffles and ceramic cylinders. All four signals from these load cells were electronically summed, amplified, and split into two equivalent signals. One signal was recorded directly; the second was electronically differentiated before being recorded. This dual arrangement gave continuous records of the weight of the fuel on the platform as well as the time rate of change of the weight.

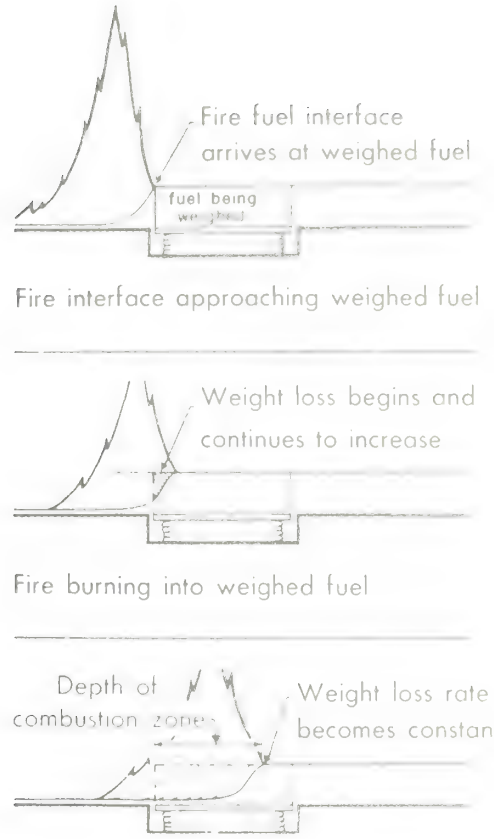
The excelsior fuel beds were 3 feet wide, 8 feet long, and 4-1/2 inches deep. The front of the weighing platform was placed 4 feet from the front of the fuel bed and centered laterally. This arrangement permitted the fire to reach a quasi-steady rate of spread before burning onto the platform. Inconsistencies in burning rate near the edges were minimized by allowing 9 inches of fuel on either side of the platform. Fuel cribs were constructed using 1/4-inch and 1/2-inch sticks; cribs were approximately 5 feet long, 3 feet wide, and 5 to 6 inches deep. The same size weighing platform was used for both the stick cribs and the excelsior beds.

The concept of a reaction zone and a reaction time can be visualized by considering the fuel-reaction zone interface as moving through the fuel on the weighing platform (fig. 9). When this interface reached the fuel being weighed, the strip chart recorder indicated the time of arrival by the start of weight loss. As the fire interface proceeded into the weighed fuel, the weight loss rate continued to increase. The length of the weighing platform was longer than the depth of the reaction zone; hence, the rate of weight loss stabilized when the fire advanced onto the platform a distance equivalent to the depth of the reaction zone. The lapsed time from initial weight loss to the onset of stabilization is the reaction time, τ_R. Reaction time determination is greatly enhanced by differentiating the weight loss signal. The major conversion of woody fuels to combustible gases occurs within this time.

In figure 10, the reaction time, τ_R, is defined on the derivative curve as the time from initial mass loss until the loss stabilizes at a steady rate. The observation of a *linear* mass loss rate during the reaction time was a surprising but consistent feature of our measurements. The duration of *constant* mass loss rate was dependent on the length of the weighing platform; it had no bearing on the duration of the reaction time.

Note also that the reaction time could be taken as the fire burned off the weighing platform. The concept of reaction time, as associated with weight loss, was first noted in this manner. However, data taken as the fire burned off the weighing platform were not as consistent as they were when it burned onto the platform.

Figure 3.--Fire-fuel interface moving through weighed fuel.



The mass loss rate, $\dot{m}$, obtained from the weight loss data, [illegible] lowing physical features:

$$\dot{m} = (w_n - w_r) RW,$$

where W equals the width of the weighing platform. The efficiency of the experimental fires can now be expressed as

$$\Gamma = \frac{\dot{m}}{w_n RW}.$$

Combining the efficiency with the reaction time, τ_R (as indicated by equation (25) and taken from the weight loss data, figure 10), gives the experimentally determined reaction velocity,

$$\Gamma = \frac{\dot{m}}{w_n RW \tau_R}. \qquad (35)$$

The potential reaction velocity is calculated [illegible] the experimentally measured reaction velocity, Γ, from the effects of the moisture and minerals of the fuels that were used in the experiments.

$$\Gamma' = \frac{\Gamma}{\eta_M \eta_s}.$$

The potential reaction velocity may now be correlated with the physical features of the fuel array.

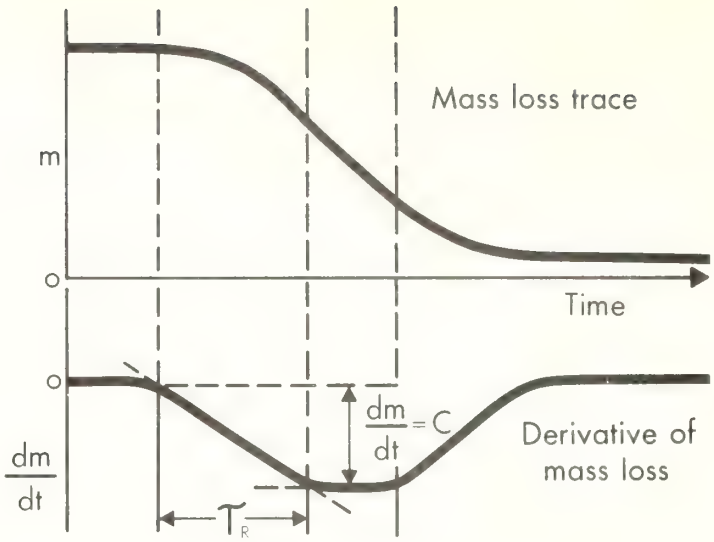


Figure 10.--Illustration of mass loss and its derivative.

Experimental Results

Reaction Velocity

The results of the experiments utilizing the derivative of the weighing system to determine reaction velocity are shown in figure 11. As expected, there was an optimum packing ratio for each of the 1/4-inch and 1/2-inch fuels. It was not possible to identify a drop in reaction velocity at very low packing ratios with the excelsior because of (a) the difficulty in constructing a fuel bed having only a few strands of excelsior per square foot, and (b) the lack of sensitivity on the weighing system at extremely light fuel loadings. However, it is evident that the reaction velocity must drop to zero if there is no fuel to support combustion, just as it does for the larger fuels.

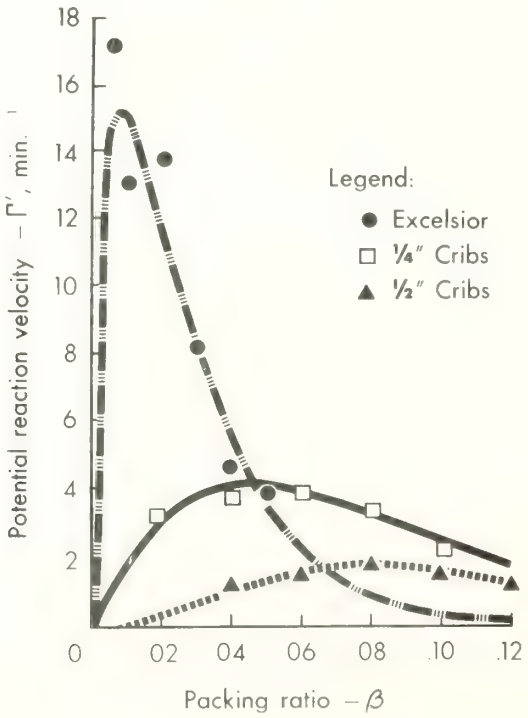


Figure 11.--Determination of correlation equation for potential reaction velocity.

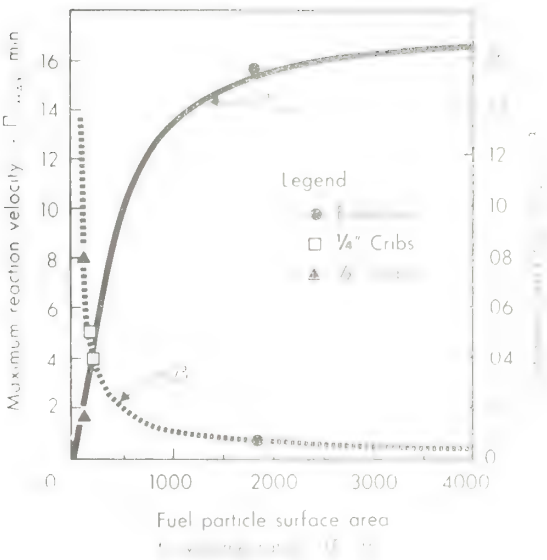


Figure 12.--Determination of optimum packing ratio.

The reaction velocity for fine fuels (excelsior, [illegible]) is much lower at the optimum packing ratio than it is for the larger 1/4-inch and 1/2-inch sticks (fig. 11). As expected, the optimum packing ratio is not the same for all fuels and increases to the right as the fuels increase in thickness. Note also that tightly packed fine fuels actually have lower reaction velocities than do larger fuels at the same packing ratio. The loss of reaction velocity of fine fuel can be seen in the field by observing the difference in flaming vigor between pine needles on a broken treetop supported above the ground and compacted pine needle litter; the latter burns with much less vigor.

The data points in figures 11 through 16 are the average of three or more replications in the excelsior, and two or more in the stick cribs.

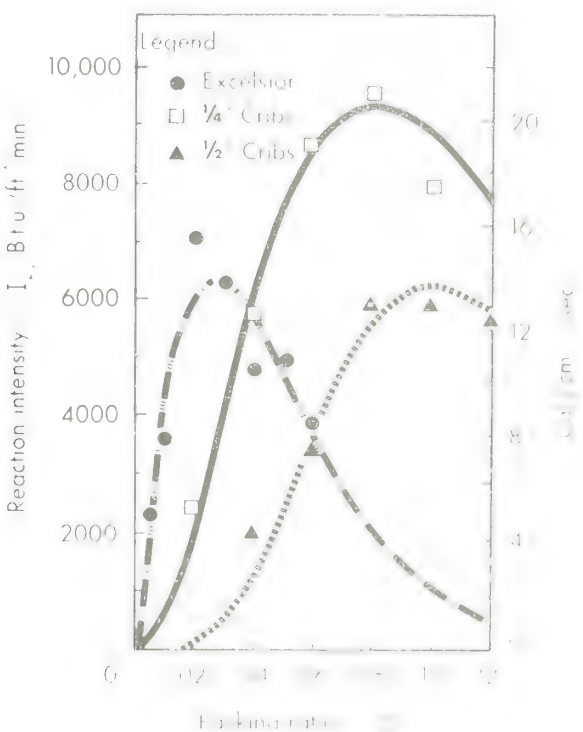


Figure 13.--Confirmation of reaction intensity equation with original data. Direct comparison of reaction intensity between fuels is not intended, nor can it be made because loading was not held constant.

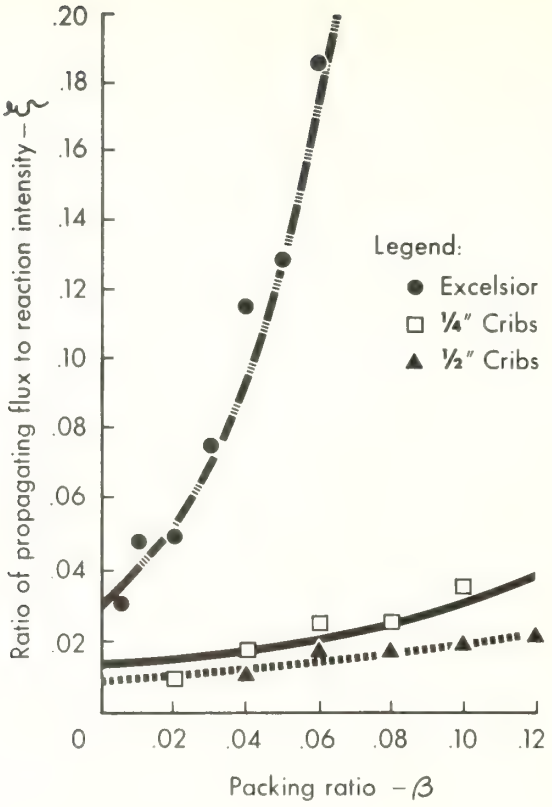


Figure 14.--Determination of propagating flux ratio, ξ.

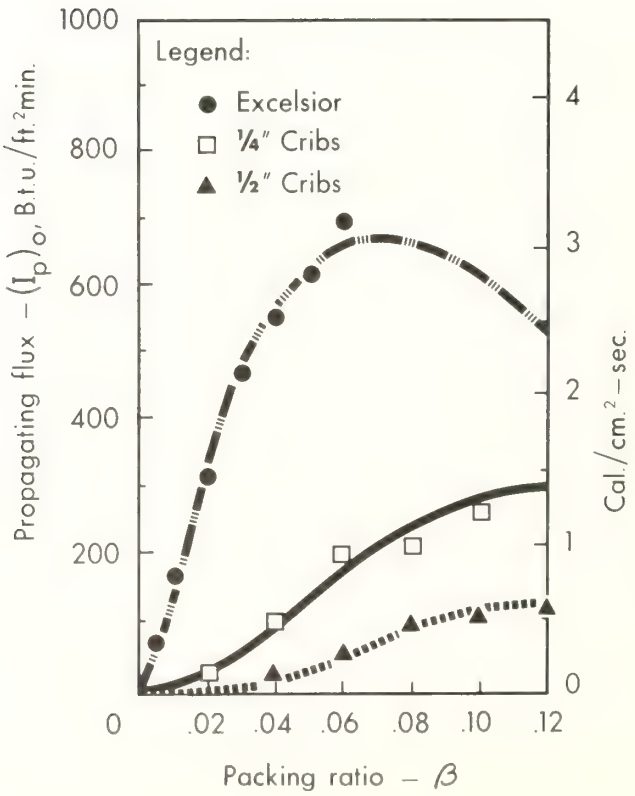


Figure 15.--Confirmation of propagating flux equation with original data.

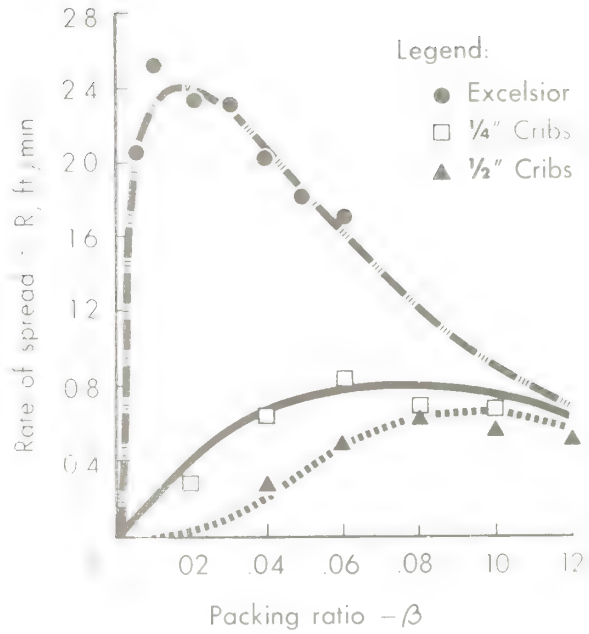


Figure 16.--Confirmation of rate of spread equation with original data.

The mathematical fit to the data of figure 11 was assumed to be a modification to a Poisson distribution. To determine the general equation as a function of both β and σ, the equations for the maximum value of Γ' and the optimum beta, β_{op}, for each fuel size were found as a function of σ (fig. 12).

$$\Gamma'_{max} = \sigma^{-1.5}/(0.495 + 0.0594\,\sigma^{-1.5}) \qquad (36)$$

$$\beta_{op} = 5.348\,\sigma^{-0.8189}. \qquad (37)$$

These were then combined with an arbitrary variable, A, to give:

$$\Gamma' = \Gamma'_{max}(\beta/\beta_{op})^{A}\exp[A(1-\beta/\beta_{op})]. \qquad (38)$$

where:

$$A = 1/(4.77\sigma^{-1}-7.27). \qquad (39)$$

The equations that relate reaction velocity, reaction intensity, propagating flux, and rate of spread were developed as a set to fit not only the dependent variable but also the data shown in figures 11 through 16. Note also that equations (36), (37), (38), and (39) will predict reaction velocity for any combination of fuel particle size, σ, and any packing ratio, β. The form of the equations has been chosen to predict reasonable values when input parameters are extrapolated beyond those tested; i.e., curves do not go negative or to infinity when they obviously should not.

Reaction Intensity

The reaction intensities are calculated from equation (23) and the data obtained from the weight loss experiments are shown in figure 13.

The correlation equations that predict the reaction velocity--(36), (37), (38), and (39)--are combined with equation (27) to predict reaction intensity for the three fuel sizes used in the experiments. The curves from these equations are also plotted in figure 13, where the fit can be compared to the original data.

Direct comparison of reaction intensity between the fuels used in the experiments is not intended, nor can it be made because fuel loading was not held constant. The study data were only intended to aid in the development of equations that could be used to predict reaction intensity and, subsequently, rate of spread over a wide range of fuel and environmental combinations.

Propagating Flux

The no-wind propagating flux is calculated from equation (6),

$$(I_p)_o = R_o \rho_b \varepsilon Q_{ig}. \qquad (6)$$

A ratio, ξ, is now computed; it relates the propagating flux to the reaction intensity:

$$\xi \equiv \frac{(I_p)_o}{I_R}. \qquad (41)$$

The values computed for ξ are plotted in figure 14 as a function of β for the three fuel sizes. The following correlation equation was found for ξ as a function of β and σ:

$$\xi = (192 + 0.259\sigma)^{-1} \exp[(0.792 + 0.681\sigma^{.5})(\beta + 0.1)]. \qquad (42)$$

The fit of the data to this equation can be seen in figure 14.

The fit of this equation to the original values of propagating flux calculated from equation (6) can be seen in figure 15. The data show that $(I_p)_o$ increases with increasing β, but at a decreasing rate. Extrapolation of equation (41) solved for $(I_p)_o$ indicates that it would actually reach a maximum and then decrease. This is a reasonable prediction, considering the fact that the fuel array is becoming so compact that the intensity has also decreased (fig. 13).

Rate of Spread

Combining the heat source and heat sink terms produces the final no-wind rate of spread equation:

$$R_o = \frac{I_R \xi}{\rho_b \varepsilon Q_{ig}}. \qquad (43)$$

Predictions from this equation are shown with the original data in figure 16.

Figure 16 illustrates the difference in spread characteristics between the fine fuel, excelsior, and the sticks. A family of curves for any particle size could be calculated, using the equations developed in this section.

EVALUATION OF WIND AND SLOPE COEFFICIENTS

To introduce wind and slope into the model, we must evaluate the coefficients ϕ_W and ϕ_S. Rearranging equation (42) with $\phi_S = 0$:

$$\phi_W = \frac{I_p}{(I_p)_{\phi=0}} - 1. \qquad (43)$$

If the fuel parameters in equation (6) are assumed constant, the propagating flux is proportional to the rate of spread and equation (44) becomes

$$\phi_W = \frac{R_W}{R_0} - 1 \qquad (44)$$

where:

R_W = rate of spread in the presence of a wind.

Similarly,

$$\phi_S = \frac{R_S}{R_0} - 1 \qquad (45)$$

where:

R_S = rate of spread up a slope.

For expediency it was assumed that no interaction existed between wind and slope.

Wind Coefficient

Rate of spread measurements in the presence of wind or on slopes in fuel arrays amenable to the no-wind model are needed to evaluate equations (45) and (46).

Fuel beds were built using three fuel sizes at packing ratios porous enough to cause flameout and compact enough to exceed natural conditions. They were burned in the large wind tunnel at the Northern Forest Fire Laboratory. The tunnel temperatures were held between 85° and 90° F.; and the relative humidities between 20 and 25 percent. Mean tunnel velocity was set at 2, 4, 6, or 8 m.p.h. The fuel beds were 4 feet wide and 12 feet long. The excelsior fuel was 4-1/2 inches deep. The stick fuels were constructed using a new method: three sticks were stapled together near the center and spread so they stood on three legs to form a double tripod, one up and one down, joined

Figure 17.--Double tripod fuel bed used in wind tunnel experiments.

at the center. These double tripods were arranged at various spacings to achieve the desired packing ratio (figs. 17 and 18). For very low packing ratios, this arrangement is far superior to the traditional crib construction because cribs with widely spaced sticks collapse when the cross members burn out.

Excelsior fuel beds must be carefully constructed to achieve the exact fuel depth or the bulk density will be altered with drastic effects on the rate of spread.

Field Data

McArthur's (1969) data on rate of spread for heading grassland fires in Australia are shown in figure 19. However, no data are available on the particle size, depth, or loading of the various areas burned; therefore, it was assumed that these values were similar to those of a typical arid grass area in the Western United States.

σ = 3,500 ft.$^{-1}$, w_o = 0.75 ton/acre, and depth = 1.0 ft.

Figure 18.--Burning double tripod fuel bed in a large wind tunnel.

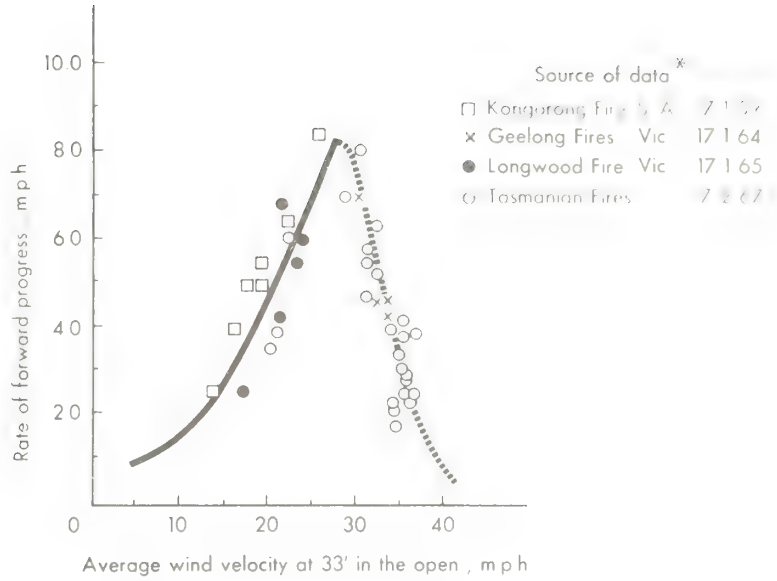


Figure 19.--Reproduction of McArthur's (1969) rate of spread data for grass.

Analysis

Before a correlation could be found between wind velocity and the multiplication factor for wind, it was necessary to find an interrelationship between ϕ_w and the fuel parameter, σ and β/β_{op}. To do this, the excelsior and 1/4-inch stick data from the wind tunnel were plotted along with McArthur's field data. Half-inch stick data did not correlate and had to be discarded. Apparently the effective bulk density is altered by the rapid heating caused by a heading fire; thus the assumption of constant fuel properties needed for obtaining equation (45) is not valid for fuels as large as one-half inch.

Another plot of the fuel parameters and multiplication factor vs. wind velocity produced the final correlation given by equation (47). Figure 20 shows the correlation parameters using the original data.

$$\phi_w = CU^B(\beta/\beta_{op})^{-E} \tag{47}$$

where:

$$C = 7.47 \exp(-0.133\sigma^{-.55}) \tag{48}$$

$$B = 0.02526\sigma^{.54} \tag{49}$$

$$E = 0.715 \exp(-3.59 \cdot 10^{-4}\sigma). \tag{50}$$

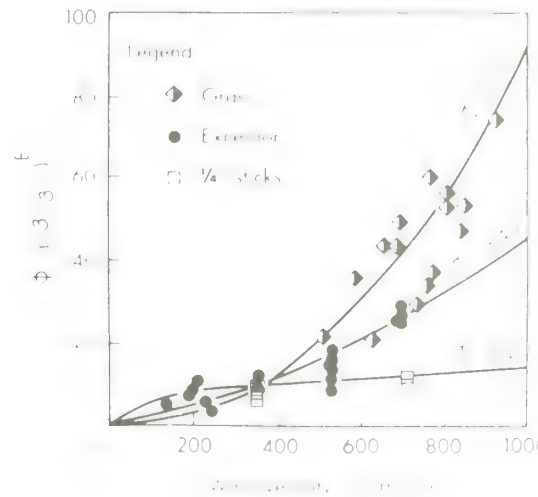


Figure 20.--Correlation parameters for determining wind coefficient.

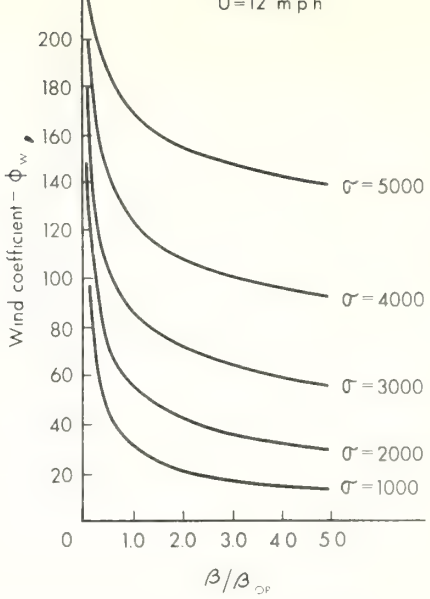


Figure 21.--Influence of packing ratio and particle size on wind coefficient at 12 m.p.h. In the absence of wind, the fuel conditions for best burning [illegible]. In the presence of wind, fires spread faster in less dense [illegible] than 1. [illegible] increases markedly as surface-area-to-volume ratio increases.

The shape of the curves is in good agreement with the concept suggested by Rothermel and Anderson (1966). At that time, it was speculated that the finer the fuel, the sharper the resulting increase in spread rate with wind velocity. As expected, fuels that were too sparse to burn well in the absence of wind will sustain a rapid fire spread when wind is applied. In effect, the optimum packing ratio shifts toward more lightly loaded fuels as wind increases. This effect is illustrated in figure 21 and can be seen in the field where sparse fuels--such as poor stands of cheatgrass--burn poorly without wind but become a flashy fuel when wind is applied.

Slope Coefficient

The effect of slope was determined for fine fuels by burning excelsior fuel beds on slopes of 25, 50, and 75 percent. The experiments were conducted in a large combustion laboratory under the same environmental conditions used for the no-wind and wind tunnel fires. Fuel was excelsior constructed at four packing ratios: 0.005, 0.01, 0.02, and 0.04. A correlation of the data is shown in figure 22. The equation for the line is

$$\phi_s = 5.275\beta^{-1.3}(\tan\phi)^2 \qquad (51)$$

where tan ϕ is the slope of the fuel bed. The final form of the rate of spread equation is

$$R = \frac{I_R(1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad (52)$$

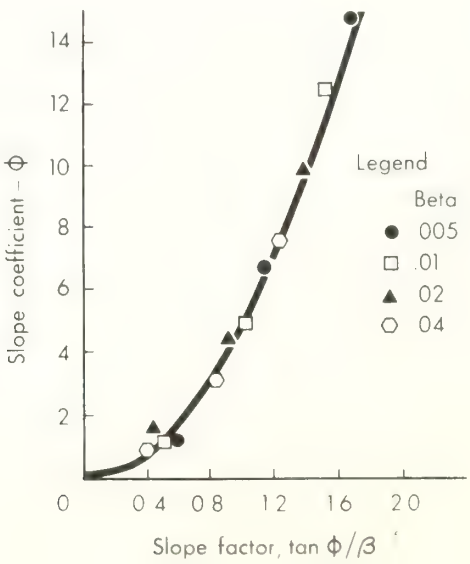


Figure 22.--Correlation parameter for slope coefficient.

SUMMARY OF FIRE SPREAD EQUATIONS

The complete set of parametric equations developed in this work is given on page 26. The required input parameters are given on page 27. These equations are easy to program for computer computations. Students of fire behavior can gain a perspective understanding of the effects of various input parameters by computing and crossplotting curve families for reaction velocity, reaction intensity, and other internal variables that govern fire spread. The equations might also be used for analyzing expected behavior of planned laboratory experiments. A word of caution--the fuel bed width must be sufficient to simulate a line fire (Anderson 1968); and the fuel [illegible] must be carefully constructed to insure a uniform distribution of the fuel elements. The equations in this form have limited use in the field because few fuel types are composed of fuels that are homogeneous in size. The remainder of this paper is devoted to adaption of the parametric equations into a mathematical model suitable for field application.

Summary of Basic Fire Spread Equations

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$ Rate of spread, ft./min. (52)

$$I_R = \Gamma' w_n h \eta_M \eta_S$$ Reaction intensity, B.t.u./ft.^{2} min. (27)

where:

$$\Gamma' = \Gamma'_{max} (\beta/\beta_{op})^A \exp[A(1-\beta/\beta_{op})]$$ Optimum reaction velocity, min.$^{-1}$ (38)

$$\Gamma'_{max} = \sigma^{1.5}(495 + .0594\sigma^{1.5})^{-1}$$ Maximum reaction velocity, min.$^{-1}$ (36)

$$\beta_{op} = 3.348\sigma^{-.8189}$$ Optimum packing ratio (37)

$$A = 1/(4.774\sigma^{.1} - 7.27)$$ (39)

$$\eta_M = 1 - 2.59 \frac{M_f}{M_x} + 5.11 \left(\frac{M_f}{M_x}\right)^2 - 3.52 \left(\frac{M_f}{M_x}\right)^3$$ Moisture damping coefficient (29)

$$\eta_S = 0.174\ S_e^{-.19}$$ Mineral damping coefficient (30)

$$\xi = (192 + 0.2595\sigma)^{-1} \exp[(0.792 + 0.681\sigma^{.5})(\beta + 0.1)]$$ Propagating flux ratio (42)

$$\phi_w = CU^B \left(\frac{\beta}{\beta_{op}}\right)^{-E}$$ Wind coefficient (47)

$$C = 7.47 \exp(-0.133\sigma^{.55})$$ (48)

$$B = 0.02526\sigma^{.54}$$ (49)

$$E = 0.715 \exp(-3.59 \times 10^{-4}\sigma)$$ (50)

$$w_n = \frac{w_o}{1 + S_T}$$ Net fuel loading, lb./ft^2 (24)

$$\phi_s = 5.275\ \beta^{-.3} (\tan \phi)^2$$ Slope factor (51)

$$\rho_b = w_o/\delta$$ Ovendry bulk density, lb./ft.^{3} (40)

$$\varepsilon = \exp(-138/\sigma)$$ Effective heating number (14)

$$Q_{ig} = 250 + 1{,}116\ M_f$$ Heat of preignition, $\frac{\text{B.t.u.}}{\text{lb.}}$ (12)

$$\beta = \frac{\rho_b}{\rho_p}$$ Packing ratio (31)

Input Parameters for Basic Equations

w_o, ovendry fuel loading, lb./ft.^{2}

δ, fuel depth, ft.

σ, fuel particle surface-area-to-volume ratio, 1/ft.

h, fuel particle low heat content, B.t.u./lb.

ρ_p, ovendry particle density, lb./ft.^{3}

M_f, fuel particle moisture content, $\frac{\text{lb. moisture}}{\text{lb. ovendry wood}}$

S_T, fuel particle total mineral content, $\frac{\text{lb. minerals}}{\text{lb. ovendry wood}}$

S_e, fuel particle effective mineral content, $\frac{\text{lb. silica-free minerals}}{\text{lb. ovendry wood}}$

U, wind velocity at midflame height, ft./min.

$\tan \phi$, slope, vertical rise/horizontal distance

M_x, moisture content of extinction. This term needs experimental determination. We are presently using 0.30, the fiber saturation point of many dead fuels. For aerial fuels (β <.02) with low wind velocity (<5 m.p.h.) $M_x \simeq 0.15$.

THE FIRE SPREAD MODEL

Rate of spread and intensity predicted by the model are based on equations (52) and (27). These equations had to be modified,however,to accept fuels that were composed of heterogeneous mixtures of fuel types and particle sizes. Such fuels as pine needle litter, grass, brush, and logging slash are the easiest to model. Patchy fuels--accumulations of broken branches, treetops, snags, foliage litter, brush, and other lesser vegetation are more difficult to model because of the discontinuous patterns in which they are found. For the model, however, these various size fuels are assumed to be uniformly distributed within the fuel array. This assumption is especially critical for the fine fuels (foliage and twigs under 1/4 inch in diameter).

It is also assumed that the fuel can be grouped into categories according to similar properties. For example, there would be one category for living fuel and a second for dead fuel. It is also desirable to have separate categories for foliage and branchwood. Grouping by species is not sufficient because foliage and branchwood can have significant differences in particle properties. A further breakdown by size class is required within these categories if the fuel particles vary greatly in size. The size classes used can be arbitrarily established but should include a class for fine fuels. Experience will show to what extent size class breakdowns are necessary. Our initial work indicates that the larger fuels have a negligible effect on fire spread; thus, these can often be eliminated from consideration.

To aid in the understanding of fuel distribution, we introduced the concept of a unit fuel cell. A unit fuel cell is the smallest volume of fuel within a stratum of mean depth that has sufficient fuel to be statistically representative of the fuel in the entire fuel complex. This concept permits the mathematical representation of the fuel distribution to be referenced to a unit fuel cell rather than to the entire complex.

Primarily, this concept aids in mathematically *weighting* input parameters. Consequently, it is not necessary to specify the size of the unit fuel cell within an area under study; rather to provide mean values per unit fuel cell which then represent the fuel complex that is being modeled. Representative inputs can be preselected to form fuel models that are tailored for analysis by the fire spread model.

The model is based on the concept that a singular characteristic parameter can be found by properly weighting the variations in the parameter in the heterogeneous mixture. To implement this concept, we had to consider how each fuel parameter in the model exerts its effect on the three characteristic features of a spreading fire: (1) The energy source; (2) the energy sink; (3) the flow of air or of heat within the array.

The processes that control combustion rate--evaporation of moisture from the fuel, transfer of heat into the fuel, and evolution of combustible gases by the fuel--occur through the surface of the fuel particle. The fuels having the highest surface-area-to-volume ratio (fine fuels) will respond the fastest; therefore, these will be involved in the leading portions of a fire. It is no revelation to firefighters or to fire scientists that fine fuels might be expected to react the fastest. However, it is not realistic to arbitrarily state that 90 percent of particles 1/8 inch in diameter and under are consumed and that some fixed ratio of the other size classes is consumed. Weighting by surface area eliminates the problem of making arbitrary decisions as to which fuel sizes to include and which not to include.

Mathematical Fire Spread Model Inputs

Mean values within i^{th} category and j^{th} size class of fuel complex:

$(\bar{w}_o)_{ij}$ = ovendry loading, lb./ft.^{2}

$(\bar{\sigma})_{ij}$ = surface-area-to-volume ratio, (ft.^{2}/ft.^{3})

$(S_T)_{ij}$ = mineral content, (lb. minerals/lb. wood)

$(S_e)_{ij}$ = effective mineral content $\frac{\text{(lb. minerals - lb. silica)}}{\text{lb. wood}}$

$(\bar{h})_{ij}$ = low heat value, B.t.u./lb.

$(M_f)_{ij}$ = moisture content, (lb. moisture)/(lb.wood)

$(\bar{\rho}_p)_{ij}$ = ovendry particle density, (lb./ft.^{3}).

Mean value within i^{th} category:

$(M_x)_i$ = moisture content of extinction (lb. moisture)/(lb. ovendry wood).

Mean fuel array properties:

$\bar{\delta}$ = depth of fuel, (ft.)

$\tan \phi$ = slope, (ft. vertical rise/ ft. horizontal).

U = wind velocity at midflame height, (ft./min.)

m = total number of categories

n = number of size classes within i^{th} category.

Formulation of Fire Spread Model

The model is now formulated from the basic equations of fire spread and the weighting concept. The basic equations are available on page 26. The detailed weighting concept must be developed.

Weighting parameters based on the surface area of the fuel within each size class and category are developed from input parameters as shown on page 29.

Let:

$\bar{A}_T$ = mean total surface area of fuel per unit fuel cell.

$\bar{A}_i$ = mean total surface area of fuel of i^{th} category per unit fuel cell.

$\bar{A}_{ij}$ = mean total surface area of fuel of j^{th} class and i^{th} category per unit fuel cell.

The mean total surface area per unit fuel cell of each size class within each category is determined from the mean loading of that size class and its surface-area-to-volume ratio and particle density.

$$\bar{A}_{ij} = \frac{(\bar{\sigma})_{ij} \; (\bar{w}_o)_{ij}}{(\bar{\rho}_p)_{ij}} \; . \tag{53}$$

The mean total surface area of the i^{th} category per unit fuel cell and the mean total surface area per unit fuel cell are then obtained by summation of the areas within each category and within the fuel cell with equations (54) and (55),

$$\bar{A}_i = \sum_{j=1}^{j=n} \bar{A}_{ij} \tag{54}$$

$$\bar{A}_T = \sum_{i=1}^{i=m} \bar{A}_i \; . \tag{55}$$

Two weighting parameters are now calculated that are used throughout the remainder of the model:

$$f_{ij} = \frac{\bar{A}_{ij}}{\bar{A}_i}$$

Ratio of surface area of j^{th} size class to total surface area of i^{th} category per unit fuel cell (56)

$$f_i = \frac{\bar{A}_i}{\bar{A}_T}$$

Ratio of surface area of i^{th} category to total surface area per unit fuel cell (57)

Using the weighting parameters, the basic fire spread equations are modified as follows:

Reaction intensity becomes:

$$I_R = \Gamma' \sum_{i=1}^{i=m} f_i (\dot{w}_n)_i \bar{h}_i (\eta_s)_i (\eta_M)_i \quad (58)$$

where the characteristic parameters weighted by surface area are:

$$(\dot{w}_n)_i = \sum_{j=1}^{j=n} f_{ij} (\bar{w}_n)_{ij} \quad \text{Net loading of } i^{th} \text{ category} \quad (59)$$

$$(\bar{w}_n)_{ij} = \frac{(\bar{w}_o)_{ij}}{1 + (\bar{S}_T)_{ij}} \quad \text{Net loading of } j^{th} \text{ class within } i^{th} \text{ category} \quad (60)$$

$$h_i = \sum_{j=0}^{j=n} f_{ij} \bar{h}_{ij} \quad \text{Low heat content value of } i^{th} \text{ category} \quad (61)$$

$$(\tilde{\eta}_s)_i = 0.174 (\tilde{S}_e)_i^{-0.19} \quad \text{Mineral damping coefficient of } i^{th} \text{ category} \quad (62)$$

$$(S_e)_i = \sum_{j=1}^{j=n} f_{ij} (\bar{S}_e)_{ij} \quad \text{Characteristic effective mineral coefficient of } i^{th} \text{ category} \quad (63)$$

$$(\tilde{\eta}_M)_i = 1 - 2.59 (r_M)_i + 5.11 (r_M)_i^2 - 3.52 (r_M)_i^3 \quad \text{Moisture damping coefficient of } i^{th} \text{ category} \quad (64)$$

$$(r_M)_i = \frac{(M_f)_i}{(M_{ext})_i} \quad \text{Moisture ratio of } i^{th} \text{ category} \quad (65)$$

$$(M_f)_i = \sum_{j=1}^{j=n} f_{ij} (\bar{M}_f)_{ij} \quad \text{Moisture content of } i^{th} \text{ category} \quad (66)$$

To complete the calculation of the reaction intensity, the potential reaction velocity, Γ', must be calculated. A single value of reaction velocity is calculated for the fuel complex.

Γ' is dependent on the packing ratio and fuel particle size. The packing ratio regulates the heat and airflow within the fuel array. This regulation of flow is dependent upon whether or not the space is occupied or vacant. Therefore the ratio should be entered as a mean value of all particle sizes. However, the surface-area-to-volume ratio is a parameter that characterizes the particle size of the fuel complex that is regulating the combustion processes in the fire front and σ must be weighted by surface area.

Applying these concepts,

$$\Gamma' = \Gamma'_{max} (\bar{\beta}/\bar{\beta}_{op})^A \exp[A(1 - \bar{\beta}/\bar{\beta}_{op})] \quad (67)$$

$$\Gamma'_{max} = (\tilde{\sigma})^{1.5}/(495 + 0.0594\ (\tilde{\sigma})^{1.5}) \quad (68)$$

$$\bar{\beta}_{op} = 3.348\ (\tilde{\sigma})^{-0.8189} \quad (69)$$

$$A = (4.774\ (\tilde{\sigma})^{0.1} - 7.27)^{-1} \quad (70)$$

where:

$$\tilde{\sigma} = \sum_{i=1}^{i=m} f_i \tilde{\sigma}_i$$

Characteristic surface-area-to-volume ratio of the fuel complex (71)

$$\tilde{\sigma}_i = \sum_{j=1}^{j=n} f_{ij} \bar{\sigma}_{ij}$$

Characteristic surface-area-to-volume ratio of i^{th} fuel category (72)

$$\bar{\beta} = \frac{1}{\bar{\delta}} \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} \frac{(\bar{w}_o)_{ij}}{(\bar{\rho}_p)_{ij}}$$

Mean packing ratio (73)

$$\bar{\rho}_b = \frac{1}{\bar{\delta}} \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} (\bar{w}_o)_{ij}$$

Mean bulk density (74)

This completes the computations necessary for calculating reaction intensity. The parameters within the basic rate of spread equation

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}, \quad (75)$$

are treated similarly.

The no-wind propagating flux ratio, ξ, is a function of the mean packing ratio and characteristic surface-area-to-volume ratio.

$$\xi = (192 + 0.2595\ \tilde{\sigma})^{-1} \exp[(0.792 + 0.681\ \tilde{\sigma}^{.5})(\bar{\beta} + 0.1)]. \quad (76)$$

In the heat sink terms, the bulk density is dependent upon bulk properties of the array: The effective heating number, ε, and the heat of preignition are dependent upon fuel surface. Therefore, the bulk properties must be separated from the particle properties when summing and weighting.

$$\rho_b \varepsilon Q_{ig} = \bar{\rho}_b \sum_{i=1}^{i=m} f_i \sum_{j=1}^{j=n} f_{ij} \left[\exp\left(\frac{-138}{\bar{\sigma}_{ij}}\right)\right] (\bar{Q}_{ig})_{ij} \quad (77)$$

where:

$$(\bar{Q}_{ig})_{ij} = 250 + 1{,}116\ (\bar{M}_f)_{ij}$$

The heat of preignition for j^{th} size class within the i^{th} category (78)

The model is completed by inclusion of the wind and slope multiplication factors:

$$\phi_W = CU^B \left(\frac{\bar{\sigma}}{\bar{\sigma}_{op}}\right)^{-E} \tag{79}$$

and: $$\phi_S = 5.275\ (\beta)^{-0.3} (\tan \phi)^2 \tag{80}$$

where:

$$U = \text{mean windspeed at midflame height, (ft./min.)} \tag{81}$$

$$C = 7.47 \exp(-.133\ \bar{\sigma}^{.55}) \tag{82}$$

$$B = 0.02526\ \bar{\sigma}^{.54} \tag{83}$$

$$E = 0.715 \exp(-3.59 \cdot 10^{-4} \bar{\sigma}). \tag{84}$$

If $\bar{\sigma} < 175$, the weighted fuel size is too large for the wind factor. ($\bar{\sigma}$ decreases as fuel size increases.) We have not found this limitation to be restrictive on any of the fuel models tested to date. The reason, of course, is that wildland fuels are composed primarily of fine fuels with consequent large values of $\bar{\sigma}$.

An upper limit is placed on the wind multiplication factor. Rothermel and Anderson (1966) found that the angle of flame tilt could be correlated to a ratio of the energy of the wind and the energy of the fire:

$$\frac{qU}{I_R J}$$

where:

q = free stream dynamic pressure lb./ft.^{2}

J = 778 ft. lb./B.t.u. - mechanical equivalent of heat

Evaluating this ratio at the limiting value of spread rate found by McArthur (1969) (fig. 20) gives:

$$\frac{qU}{I_R J} = 5.2 \times 10^{-5}. \tag{85}$$

Assuming air temperature and density for a nominal summer day, T = 80° F., elevation = 3,000 ft.; this reduces to,

$$\frac{U}{I_R} = 0.9. \tag{86}$$

This limit is taken for $(\phi_W)_{max}$.

If $\frac{U}{I_R} > 0.9$, then $\phi_W = \phi_W$ at $U = 0.9\ I_R$. (87)

APPLICATION TO THE FIELD

The mathematical model has application to management problems in two situations:

1. The "hypothetical fire" situation in which operations' research techniques are utilized for fire planning, fire training, and fuel appraisal.

2. The "possible fire" situation for which advance planning is needed, such as fire-danger rating and presuppression planning. Predictions of potential fire severity for possible management practices (i.e., methods of thinning, slash treatment, and prescribed burning) have the potential for being the most valuable contribution that fire modeling can perform.

A third situation--forecasting the behavior of existing wildfires--will require a greater degree of sophistication than this model and our knowledge of fuels will permit at the present time. Variations in fuel and weather cause departures from predicted spread and intensity that pose risks unacceptable in fire suppression activities. A method for forecasting the behavior of a specific fire eventually will be developed; most likely, it will be patterned on a probability basis similar to that used for forecasting weather. To accomplish this, a technique must be developed for rapidly updating fuel inventories on the threatened site.

Choosing input parameters for the model from the infinite variety of fuel and environmental arrangements and combinations seems almost overwhelming. However, patterns in the growth of vegetation exist that can be utilized to greatly simplify the inventory process. It also proves helpful to group the inputs in the following manner:

1. Fuel Particle Properties

   - Heat Content
   - Mineral Content
   - Particle Density

2. Fuel Array Arrangement

   - Loading by Size Class--Living and Dead
   - Mean Size Within Each Class--Surface-Area-To-Volume Ratio
   - Mean Depth of Fuel

3. Environmental Related Values

   - Wind Velocity
   - Fuel Moisture Content
   - Slope

The fuel particle properties are not expected to vary greatly within vegetation types. Such values can be readily determined in the laboratory and assembled in a manner that should have wide applicability.

Fuel array arrangement patterns must be determined in the field. These inventory tasks will be more difficult than measuring fuel particle properties. However, it is expected that patterns will be found that are repeatable within the limits necessary for calculating potential fire hazard using the model. The fuel type, age of stand, exposure, soils, rainfall patterns, and fire history may be used as indexes for cataloging fuel arrangement patterns. Broader classification by ecotype or habitat will also prove valuable for sorting out fuel parameters.

The environmental related parameters can be inserted to investigate the effect of the range of wind, moisture, or slope that might be expected to be imposed upon the fuels being modeled.

Fuel Models and Application

On-the-spot sampling of all input parameters is costly, time consuming, and tedious. Cataloging fuel properties and relating them to observable site characteristics does not eliminate the fuel sampling process, but it will permit a wide application of sampling results. These results can be further refined for use in the mathematical model by assembling them into *fuel models* that represent typical field situations. Such fuel models contain a complete set of inputs for the mathematical fire spread model.

Land managers can be trained to choose the fuel model that is most applicable to the fuels and climate for their areas of interest. If further refinement is desired, internal properties (e.g., fuel loading in logging slash, the ratio of dead-to-living fuel in brush, and the amount and type of understory in timber) of each fuel model could be tailored to permit the model to more closely match specific fuels.

Work has already begun on fuel models for the National Fire-Danger Rating System. Eleven fuel models (table 1) have been assembled that represent a large portion of the forests, brush fields, and grasslands found in the temperate climates of North America.

The variations in spread and intensity between fuel types as predicted by the model may readily be seen from results obtained from computations with the 11 fuel models as inputs. To assist in understanding the sensitivity of the inputs, the fuel *particle* properties have been held constant and the variations among fuel types may be attributed to the loading by size class and fuel depth as shown in table 1. The fine fuel of the *living fuel* category is all that is assumed to enter into the reaction. To obtain reasonable values of reaction intensity for fuel models that contain living fuels, the moisture of extinction value for the living fuel must be adjusted to a higher value than that used for the dead fuels. Very little research has been done on the burning of living fuels. Philpot and Mutch (1971) suggest that crowning potential in ponderosa pine and Douglas-fir forests of Montana may be dependent upon the higher content of ether extractives (waxes, terpenes, and oils) that do not require pyrolysis for producing the combustible constituents. It also appears that the proportion of dead fuels within a fuel complex has an influence on how much of the living fuel burns. Fosberg and Schroeder (1971) provide a formulation for predicting the moisture of extinction of living fuels based on the ratio of living-to-dead fuels and the moisture content of the find dead fuel.

$$(M_x)_{living} = \left(\frac{2.5}{\alpha}\right)\left[1 - \frac{\alpha}{2.5}(M_f)_{dead}\right]$$, with lower limit of 0.01, (88)

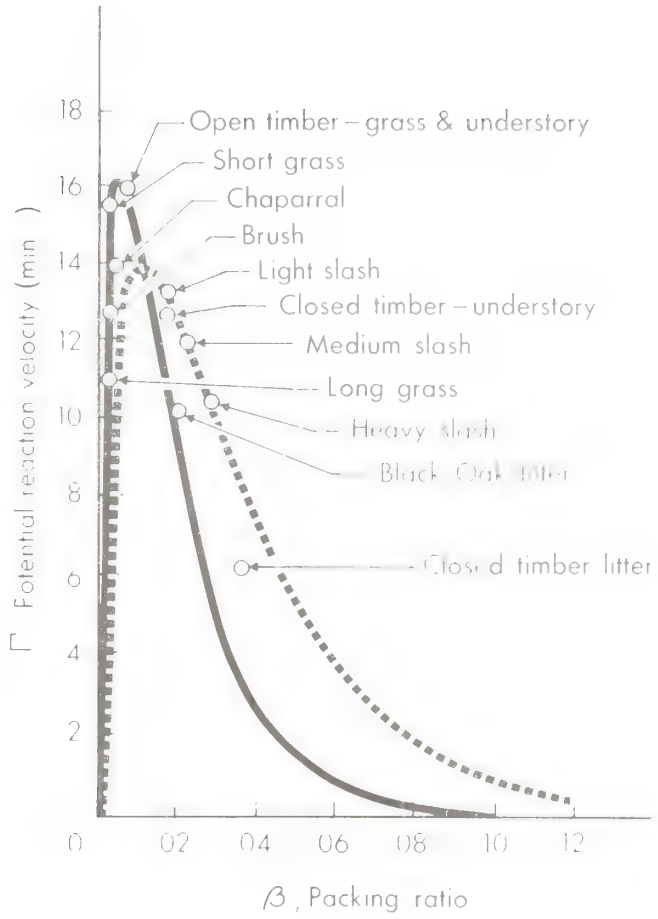
where: α = ratio of mass-of-fine-live-fuel to mass-of-total-fine-fuel; fine fuel is taken as fuel ≤1/4-inch diameter. $(M_f)_{dead}$ = moisture content (fraction, not percent) of fine dead fuel.

Table 1.--*Values for input parameters of 11 preliminary fuel models for the National Fire-Danger Rating System*[1]

Fuel types	Total loading	Dead fuel						Living fuel		Fuel depth
		Fine		Medium		Large				
		σ	w_o	σ	w_o	σ	w_o	σ	w_o	
	Tons/acre	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*
Grass (short)	0.75	3,500	0.034	--	--	--	--	--	--	1.0
Grass (tall)	3.0	1,500	.138	--	--	--	--	--	--	2.5
Brush (not chaparral)	6.0	2,000	.046	109	0.023	--	--	1,500	0.092	2.0
Chaparral	25.0	2,000	.230	109	.184	30	.092	1,500	.230	6.0
Timber (grass and understory)	4.0	3,000	.092	109	.046	30	.023	1,500	.023	1.5
Timber (litter)	15.0	2,000	.069	109	.046	30	.115	--	--	0.2
Timber (litter and understory)	30.0	2,000	.138	109	.092	30	.230	1,500	.092	1.0
Hardwood (litter)	15.0	2,500	.134	109	.019	30	.007	--	--	0.2
Logging slash (light)	40.0	1,500	.069	109	.207	30	.253	--	--	1.0
Logging slash (medium)	120.0	1,500	.184	109	.644	30	.759	--	--	2.3
Logging slash (heavy)	200.0	1,500	.322	109	1.058	30	1.288	--	--	3.0

[1] For all models $S_t = 0.0555$, $S_e = 0.010$, h = 8,000 B.t.u./lb., $\rho_b = 32.0$ lb./ft.^{3}, $(M_x)_{dead} = 0.30$, $(M_x)_{living}$ determined by equation 88.

velocity of typical wildland
... represent the extreme values of
... other for heavy logging
slash.



The effect of the change in fuel arrangement on potential reaction velocity is shown in figure 23. The flashy fuels (grass and brush) have the highest values; the closed timber litter has the lowest. Note that the grass and brush lie to the left of the optimum packing ratio under no-wind conditions. Inasmuch as one of the effects of wind is to shift the optimum packing ratio to the left, these fuels will burn extremely well under windy conditions.

The prediction of reaction intensity for the 11 fuel models is shown in figure 24 for fuel moisture ranging from 0 to extinction. All fuel models extinguish at M_x = 0.3, which is the value set by M_x for the dead fuel. The higher order variations for some fuel models are caused by the living fuel component's inability to burn when the dead fuel moisture becomes high. This is attributable to Fosberg and Schroeder's formulation (equation 88).[1]

The prediction of rate of spread is shown in figure 25 at M = 0.04 (4 percent moisture content) in the dead fuel over a range of windspeeds from 0 to 12 m.p.h. (1,056 ft./min.) at the midflame height. Comparison between figures 24 and 25 reveals the sensitivity of the model to changes in fuel arrangement and the apparent agreement of the model to what can be expected qualitatively between the fuel models. The closed timber litter and the short grass have similar and low reaction intensities. However, the rate of spread differs dramatically for the two models in the presence of wind; the grass has the highest rate of spread, the litter the slowest. This is attributed to the contrast in porosity of the two fuels (β = 0.001 for grass, and β = 0.036 for the litter). This example illustrates the common misconception that rate of spread and reaction intensity are directly related.

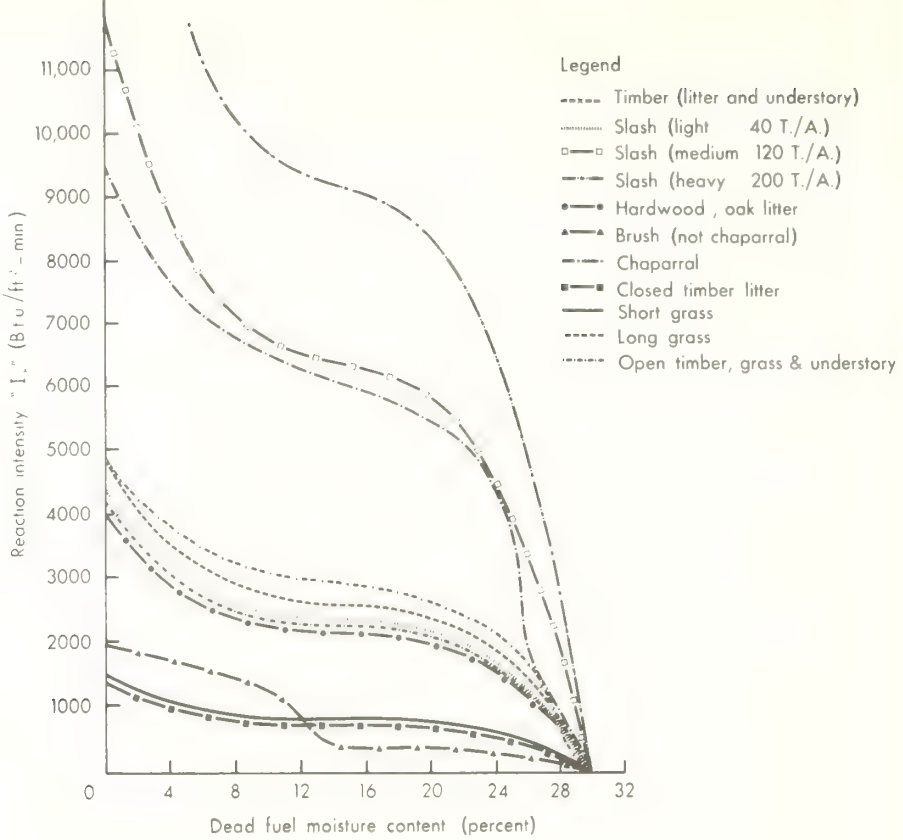


Figure 24.--Reaction intensity of typical wildland fuels computed with heterogeneous formulations for the model from data in table 1.

Heavy logging slash has by far the highest reaction intensity but a medium rate of spread; chaparral has both a high reaction intensity and a high rate of spread. It is gratifying that the model predictions are high in both values because the model was designed to represent the brush fields of the Southwest. These brush fields pose a severe fire hazard (Countryman, Fosberg, Rothermel, and Schroeder 1968).

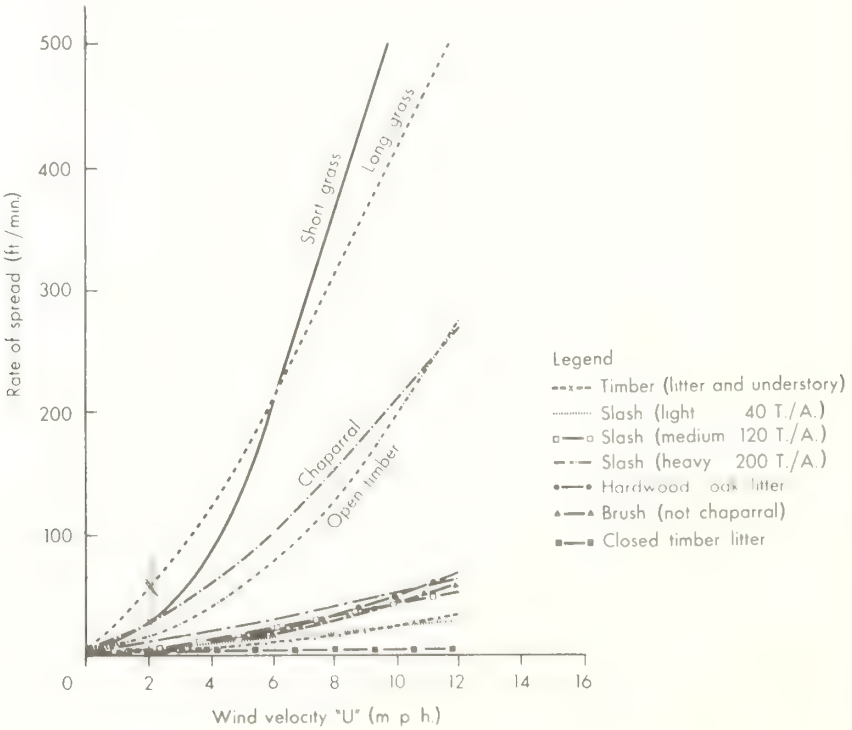


Figure 25.--Rate of spread of typical wildland fuels computed with heterogeneous formulations for the model from data in table 1 at M_f = 0.04 (4 percent moisture content) and windspeed = 12 m.p.h.

Figure 26.--Effect of moisture and minerals on rate of spread in a hypothetical fuel model.

The positions of the curves in both figures (1 and 2) and relative particle properties (h, ρ_p, S_e, M_x) of the actual fuels were used to determine the values that were used in the fuel models.

To illustrate the relative effect of minerals and moisture on rate of spread, a typical homogenous fuel was chosen and rate of spread versus moisture was plotted (fig. 26). No attempt other than to discount silica was made to distinguish between the effects of different minerals.

Figure 27 illustrates the usefulness of the model to appraise fuels for management decisions. This figure shows the change in spread and intensity that could be expected in logging slash if it were burned under no-wind and 10 percent moisture conditions at various stages in decomposition. The ability of the model to predict fire severity as reflected in figure 27 should offer new opportunities for resource managers to integrate fuel management into resource planning activities.

Figure 27.--Change in spread and intensity in logging slash after aging. 1. New--when it had dried but retained its needles; 2. Intermediate--after sufficient aging to remove 50 percent of the needles and the depth of fuel had settled to 75 percent of its original value; 3. Old--sufficient aging to remove 100 percent of the needles and the depth of the fuel had settled to 50 percent of its original value.

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FIELD TEST OF A RATE-OF-FIRE-SPREAD MODEL IN SLASH FUELS

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Abstract

Predicted rates of fire spread using a mathematical model were consistently greater but in reasonably close agreement with rates observed on test fires in ponderosa pine and Douglas-fir slash. Fuel loading, bulk density, particle density, particle surface-to-volume ratio, heat content, total plant salt content, silica-free salt, fuel moisture, and wind velocity were determined as input variables for the test on plots containing slash with and without needles, and at two loadings and three depths. Fuel discontinuities and inadequate knowledge of fuel moisture contents that limit ignition are discussed as the primary reasons for the deviations. One-half of the total fuel weight loss in the flame front was accounted for by particles less than 1 cm. in diameter. A multiple regression for predicting flame length is provided.

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INTRODUCTION

Development of a mathematical model for predicting rate of fire spread is part of an effort at the Northern Forest Fire Laboratory to formulate a system for appraising the fire behavior potential of fuel. Desirable features of such a fuel appraisal system are quantitativeness, predictability, and flexibility.

A fuel appraisal system based upon quantitative inputs and outputs is needed for objectively guiding fire management decisions. Appraisal of the fire spread potential of fuel can help with evaluations of silvicultural treatments, prevention and presuppression planning, budgeting of fire control expenditures, fire simulation training, and wildfire suppression.

Earlier and existing systems of fuel appraisal, of which Hornby's (1935) is the best known and most widely used, have been useful, but contain weaknesses that limit their application for current and future resource management. The major weaknesses seem to involve the following:

1. A fixed level of fire-weather severity is required for making the evaluations. "Average bad" conditions are assumed. Usually fuels are considered quite dry and winds rather strong.

2. Seasonal and yearly changes in the amount and arrangement of fuel cannot be accommodated.

3. Prediction of fire behavior using changing fuel and weather conditions is not possible.

4. The systems are qualitative. They require experienced people to assess the fuels providing a precise meaning only to those closely familiar with the fuels.

A quantitative basis for fuel appraisal, such as provided by a mathematical model, facilitates uniform interpretation of appraisals and makes predictability and flexibility possible. Predictability permits assessment of anticipated land management practices upon the vegetation as fuel. For example, the fuel conditions created by harvesting and thinning could be predicted and appraised before cutting, and plans formulated for proper treatment of the expected hazard. Flexibility means that the application of fuel appraisals could be as broad or specific as desired, depending on the fuel characteristics used as modeling input and their representativeness.

A system of fuel appraisal consists of two phases: (1) Measurement and description of fuel properties required as input to the system; and (2) rating the fire behavior potential indicated by the fuel properties. This paper concerns the second phase; specifically, it reports on tests to determine the accuracy of a mathematical rate-of-fire-spread model designed by Rothermel (1972).

THE RATE-OF-SPREAD MODEL

Rothermel's rate-of-spread model is summarized by the following equation:

$$\text{Rate of spread, } R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad (1)$$

where:

I_R = reaction intensity or the rate of energy release in the flame front of a fire B.t.u./ft.^{2}-min.

ξ = propagating flux ratio--the proportion of I_R required for propagation of a no-wind fire, dimensionless

ϕ_w = multiplying factor for the effect of wind, dimensionless

ϕ_s = multiplying factor for the effect of slope, dimensionless

ρ_b = bulk density of fuel, lb./ft.^{3}

ε = effective heating number which expresses the proportion of fuel that is heated to ignition temperature dimensionless

Q_{ig} = heat of preignition, the heat required to bring a unit weight to ignition, B.t.u./lb.

These terms are computed from a set of rather complex equations. This set, which is summarized in equation (1), constitutes the mathematical model. The basic fuel and environmental input variables for the model are shown in table 1.

Table 1.--*Fuel and environmental inputs that determine values for the terms in the rate-of-fire-spread equation*

Input variables	Terms in the spread equation						
	I_R	ξ	ϕ_w	ϕ_s	ρ_b	ε	Q_{ig}
Loading, lb./ft.^{2}	X	X	X	X	X		
Heat content, B.t.u./lb.	X						
Fuel particle density, lb./ft.^{3}	X	X	X	X			
Fuel particle surface-to-volume ratio, ft.^{2}/ft.^{3}	X	X	X			X	
Depth of fuel, ft.	X	X	X	X	X		
Fuel moisture content, fraction of dry wt.	X						X
Total salt content, fraction of dry wt.	X						
Silica-free salt content, fraction of dry wt.	X						
Wind velocity, ft./min.			X				
Angle of slope				X			

The model was developed from data gathered using controlled laboratory combustion facilities, fuel beds comprised of uniformly distributed dead fuel particles of a single size, and quasi-steady-state fire. Conditions were varied to show the effect of fuel depth, loading, particle size, windspeed, and slope. The effect of fuel moisture and mineral content was taken from other work.

Predictions of fire spread and flame front intensity using the model should apply most accurately to surface fires in uniform distributions of such fuels as needle litter, grass, logging slash, and perhaps crowning fires in brush. Less accurate predictions would be expected for patchy distributions of fuel.

The model pertains to fire spread by a flaming fire front. Fire propagation from spotting, fire whirls, and blowup conditions is not a part of the model. The model was designed for fuel appraisal, fire-danger rating, and presuppression planning where relative fuel and fire behavior evaluations are useful. Accurate fire behavior predictions for specific fires will require further refinement of the model and understanding of fuels.

Application of the model to heterogeneous fuels--fuels containing more than one size of fuel--requires recognition of the contribution to fire spread made by each kind and size class of particle. This is accomplished by entering the input variables as mean values weighted by surface area of each kind and size class of fuel particle. A complete explanation of the model and its development is given by Rothermel (1972).

PROCEDURES

Observed and predicted rates of fire spread were compared using test fires on an old bed of the Clark Fork River east of Missoula, Montana (fig. 1).

Plots 8 by 30 feet were prepared using logging slash hauled by truck as the fuel. All other vegetation was cleared from the plots. Slash was used as a test fuel because it (a) often is a hazard and silvicultural problem of considerable concern to land managers, (b) cannot be readily tested in a laboratory, and (c) provides a test of the spread model using heterogeneous fuel for which only theory exists.

Slash of two species, Douglas-fir *(Pseudotsuga menziesii* var. glauca (Beissn.) Franco) without needles and ponderosa pine *(Pinus ponderosa* Laws.) with needles, was used at three depths for each of two loadings. Each combination of species loading and depth was replicated twice, making a total of 24 plots. Two extra plots were constructed for training but were not needed for this purpose so that 13 test fires were burned for each species. The loadings and depths are within a range that is often encountered in slash.

The plots were on a zero slope and were burned under low wind velocities. A test of the spread model at high wind velocities was not possible. Fairly low fuel moisture contents were sought and obtained on all fires.

The plots were loaded uniformly with weighed amounts of slash providing conditions of approximately 15 and 30 tons per acre. Immediately after weighing and loading, the plot moisture content was sampled by ovendrying needles and branches from several diameter size classes. The moisture estimates (with standard errors within 4.9 and 8.6 percent of mean values for Douglas-fir and ponderosa pine, respectively) permitted precise estimation of the actual ovendry weight of fuel. The slash on some plots was buoyed with wire to provide desired fuel depths.

Figure 1.--Plots 8 by 30 feet were constructed on an old bed of the Clark Fork River. Wire strung between steel fenceposts supported the slash at specified depths.

Measurement of Spread Model Inputs

Loading by fuel particle size class.--The amounts of fuel in 0- to 1-, 1- to 3-, and 3- to 5-cm. diameter size classes and the needle class for ponderosa pine were calculated from sample determination of the proportions of total fuel in each size class (fig. 2).

Three branches per plot were randomly collected, dissected into the size classes, and the proportions of total branch weight were determined for each size class. These proportions were used to calculate fuel weights by size class for ponderosa pine because the proportions appeared to be the same on all plots. The amount of fuel in each size was actually sampled on each Douglas-fir plot using the planar intersect technique (Brown 1971) because the amount of 0- to 1-cm. size class material appeared to vary considerably from plot to plot.

Particle surface-area-to-volume ratios.--For the 0- to 1-cm. Douglas-fir, an average particle surface-area-to-volume ratio (σ) was determined by taking random diameter measurements. For a cylinder, σ is 4 divided by the branch diameter. Diameters for the ponderosa pine and the other Douglas-fir size classes were taken at 10-cm. intervals along the three sample branches per plot. Standard errors of the estimate averaged 2.9 percent of the mean diameters for both species and all size classes. The σ for needles was obtained from measurements on needle cross sections (Brown 1970).

Depth.--Twenty-four measurements of depth were systematically taken just prior to ignition of each plot. Standard errors of the estimate ranged from 1 to 5 percent of the mean depths. Depth values were used to compute packing ratios. The packing ratio is the ratio of fuel volume-to-volume occupied by fuel and it indicates compactness of the fuel for internal calculations in the spread model.

Figure 2.--Variations existed in sizes and arrangements of particles, as shown for ponderosa pine (top) and Douglas-fir (bottom), even though all plots were loaded as uniformly as possible. Clumps of particles exist because of the nature of branching and foliation.

Particle density.--Density values were determined from 12 randomly picked samples from each species and diameter size class. A mercury pycnometer furnished the density values for the needles and 0- to 1-cm. size classes. For the other size classes, volumes for calculating density were determined using average diameters and a length of 15 cm. for the samples. Average diameters were based on two measurements taken perpendicularly at 1-cm. intervals. Weights were on an ovendry basis and volume on an air-dry basis. Standard errors of the estimate were less than 4 percent of the mean density values for each size class.

Low heats of combustion, total ash content, and silica-free ash content.--Duplicate determinations for three samples picked randomly from the slash provided these values for needles and the 0- to 1- and 1- to 5-cm. size classes.

Moisture content.--Six samples for each size class, three near the top and three near the bottom of the slash, were collected just prior to ignition. The branchwood was ovendried and the needles subjected to xylene distillation. Standard errors for each plot ranged from 3-1/2 to 5 percent of the mean moisture contents.

Wind.--Wind velocity was measured at the expected midflame height close to each plot but away from indraft influences of the fires. Anemometers (having a threshold of 0.5 m.p.h.) connected to portable battery-operated recorders furnished the measurements. A wind vane also placed at midflame height recorded wind direction.

Temperature and relative humidity.--Temperature and relative humidity were measured just prior to ignition and continuously. They were recorded for reference but were not required for calculations in the spread rate model.

Measurement of Fire Variables

The plots were ignited across one end and allowed to burn for 5 feet to attain a quasi-steady state before spread rate measurements were begun. Time for the fire to burn between 2-foot intervals was recorded over a 20-foot distance (fig. 3).

Reaction intensity was determined from:

$$I_R = \left(\sum_{i=1}^{n} \eta_i w_i h_i\right)/\tau \qquad (2)$$

$$\tau = D/R \qquad (3)$$

where:

τ = reaction time of flame front (time for propagating flame to pass a fixed point), min.

η = average fractional weight loss of fuel in flame front

w = loading, lb./ft.^{2}

h = low heat yield, B.t.u./lb.

i = index for particle size classes

D = flame depth, ft.

R = rate of fire spread, ft./min.

Figure 3.--Rate of spread was recorded as the time taken for the leading edge of the fire to pass each of the markers shown, which were spaced 2 feet apart.

Ovendry weights, which were obtained before and after the burns, permitted calculation of the particle weight loss within the propagating flame front. Weight loss by particle size class (η) was estimated at one location in each plot. Two 15-cm.-long sample branches per size class were tagged and located in a 20- by 100-cm. area 1.5 m. from the end of each plot. The fires were quickly extinguished using a water fog after the rear of the propagating flame passed over the particles.

Flame length and depth were measured on photographs of the fires' profiles taken at 2-foot intervals along the plots. Flame length is the distance from the outermost tip of the unbroken flame to the center of the flame base which lies at the top of the fuel. Flame depth is the horizontal distance through the base of the flame from the leading edge of the flame to a point at the rear where it tapers rapidly into a low and often sporadically flaming region.

BROWN JAMES K.

1972. Field test of a rate-of-fire-spread model in slash fuels, USDA Forest Serv. Res. Pap. INT-116, 24 p., illus.

Predicted rates of fire spread using a mathematical model requiring nine input variables were consistently greater but in reasonably close agreement with rates observed on test fires in slash of two species and at two loadings and three depths. Fuel discontinuities and inadequate knowledge of fuel moisture contents that limit ignition are discussed as the primary reasons for the deviations. One-half of the total fuel weight loss in the flame front was accounted for by particles less than 1 cm. in diameter. A multiple regression for predicting flame length is provided.

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RESULTS AND DISCUSSION

Good control over the fuel variables (see tables 2 and 3) was maintained by careful construction of the plots and by obtaining high precision in estimating them.

Rate of Fire Spread

The mathematical model predicted rates of spread that were higher than observed rates on all but three of the plots (fig. 4 and table 4). Deviations (predicted values minus observed values divided by observed values) ranged from -14 to 580 percent. The average overprediction (percent deviation) was 82 for the ponderosa pine plots and 121 for the Douglas-fir plots. These are in reasonably close agreement considering the complexity of the mathematical model and the slash fuels.

Several reasons beyond experimental error probably account for the deviations. The consistent overestimate of the spread rates indicates bias that could be explained by certain aspects of the mathematical model: (1) Assumptions about the fuel; (2) the moisture of extinction chosen for the slash; and (3) the method of weighting input parameters by fuel surface area.

Some bias may have been introduced on the plots having higher intensity fires (some of the 30-ton-per-acre plots) because the 8-foot plot width limited flame development. However, this bias should be small. An analysis of the effects of plot width on flame size and related rate of spread indicates that an 8-foot plot width would retard only slightly the rate of spread for fires having flames greater than 4 feet in length (Anderson 1968). No retardation of spread rate was indicated for fires having flames less than 5 feet in length.

Table 2.--*Average fuel properties of the slash according to species and size class*

Fuel property	Ponderosa pine				Douglas-fir		
	Needles	0-1	1-3	3-5	0-1	1-3	3-5
		cm.	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*
Low heat value[1/] (B.t.u./lb.)	8,826	9,274	8,885	8,885	8,898	8,691	8,691
Silica-free ash[1/] (fraction of dry weight)	.0155	.0123	.0086	.0086	.0145	.0097	.0097
Total ash[1/] (fraction of dry weight)	.0387	.0155	.0096	.0096	.0166	.0108	.0108
Particle density (lb./ft.^{3})	31.8	35.6	33.0	30.8	[2/] 34.8	[2/] 34.8	32.3
σ (ft.^{2}/ft.^{3})	1,756	156	73.5	32.9	393	80.7	29.6
Proportion of total loading (percent)	22	7	43	28	[3/] 27	[3/] 26	[3]47

[1]Branchwood for the 1-3 and 3-5 cm. size classes was combined for the chemical analyses.

[2]Density values for the 0-1 and 1-3 cm. size classes were not significantly different using a Tukey test at the 0.05 confidence level.

[3]These values were not used to determine loadings for the spread calculations. Instead, loadings by size class were sampled for each plot.

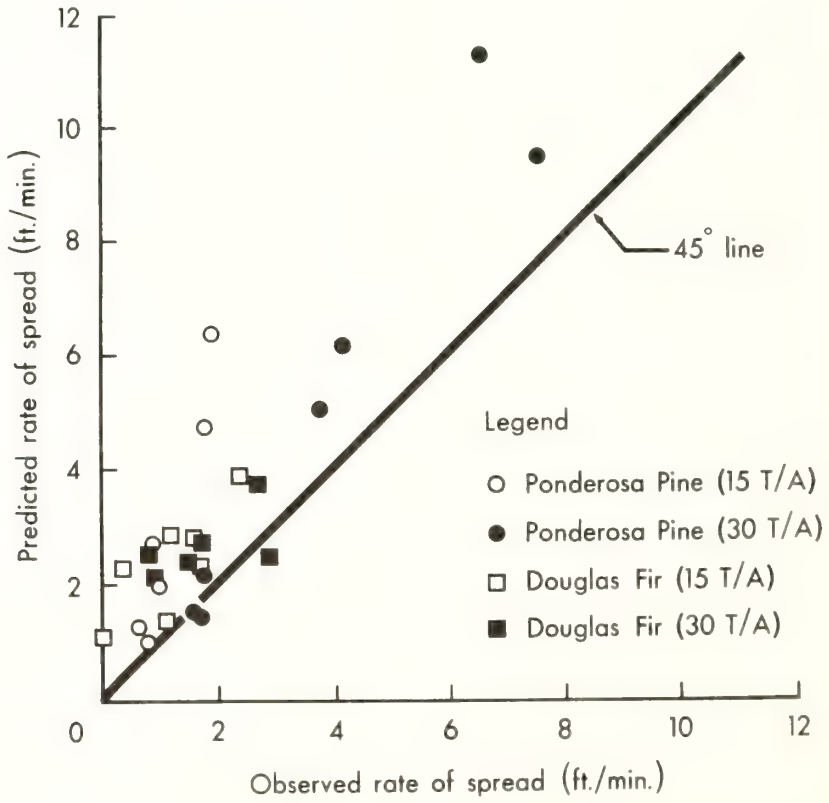

Figure 4.--Comparison between observed and predicted rates of spread for all plots.

Table 3.--*Fuel properties and environmental conditions for each plot at the time of burning*

Species	Plot number	Loading					Moisture content[1]				Fuel depth	Time	Temperature	Relative humidity	Windspeed
		Needle	0-1	1-3	3-5	Total	Needle	0-1	1-3	3.5					
		Lb./ft.²					*Percent*				*Ft.*	*Hr.*	*°F.*	*Percent*	*Ft./min.*
Ponderosa pine	1	0.32	0.10	0.61	0.40	1.43	8.0	8.0	8.0	8.0	2.74	0845	56	62	211
	2	.16	.05	.30	.20	.71	7.7	7.7	7.7	7.7	1.55	0745	52	76	150
	3	.32	.10	.61	.40	1.43	6.8	8.4	8.4	8.4	1.67	0800	48	74	185
	4	.16	.05	.30	.20	.71	5.5	7.5	7.5	7.5	1.07	2100	65	38	70
	6	.32	.10	.61	.40	1.43	6.3	7.6	7.6	7.6	1.07	2100	68	50	70
	7	.16	.05	.30	.20	.71	6.0	6.0	7.2	7.2	.65	2000	74	38	106
	8	.32	.10	.61	.40	1.43	7.3	8.8	8.8	8.8	2.92	0700	46	83	97
	9	.16	.05	.30	.20	.71	7.7	7.7	7.7	7.7	1.82	0845	53	60	167
	10	.32	.10	.61	.40	1.43	7.5	7.5	7.5	7.5	1.73	1100	75	36	308
	11	.16	.05	.30	.20	.71	6.5	6.5	6.5	6.5	1.17	2000	78	35	106
	21	.32	.11	.62	.41	1.46	5.8	5.8	5.8	9.4	.93	2100	75	27	176
	23	.18	.06	.36	.24	.84	6.9	9.0	9.0	9.0	.65	0800	51	77	97
	26	.27	.09	.51	.34	1.21	11.0	8.5	8.5	11.0	.87	0800	46	67	154
Douglas-fir	5		.11	.18	.52	.81		9.1	9.1	9.1	.77	1110	73	30	273
	12		.21	.37	1.05	1.63		8.8	8.8	8.8	1.40	1930	82	27	211
	13		.13	.34	.35	.82		9.5	9.5	9.5	.64	1630	69	27	475
	14		.30	.33	1.00	1.63		9.6	9.6	6.0	1.56	1900	87	24	88
	15a		.18	.26	.39	.83		7.6	7.6	7.6	1.29	2000	75	27	220
	15b		.18	.26	.39	.83		7.6	7.6	7.6	1.29	2015	75	27	114
	16		.27	.44	.14	.85		6.4	7.6	7.6	.92	1915	84	21	114
	17		.27	.67	.72	1.66		11.0	8.3	11.0	1.23	0700	44	85	132
	18		.34	.66	.67	1.67		10.6	10.6	10.6	1.28	0830	55	66	141
	20		.35	.39	.90	1.64		7.9	7.9	7.9	1.04	2000	76	28	185
	22		.17	.42	.25	.84		6.2	9.1	9.1	.51	2000	81	16	158
	24		.27	.60	.78	1.65		9.8	9.8	9.8	1.05	1100	73	38	211
	25		.17	.40	.26	.83		8.9	10.9	10.9	.59	1600	81	24	88

[1]Means for each size class that were not significantly different using Tukey's honestly significant difference test at the 0.05 confidence level were combined.

Table 4.--*Rate of spread, flame length, and flame depth for individual plots*

Plot	Rate of spread		Flame length	Flame depth[1]
	Observed	Predicted		
	Ft./min.	*Ft./min.*	*Ft.*	*Ft.*
		PONDEROSA PINE		
1	6.57	11.23	5.3	3.9
2	1.75	4.71	1.9	1.3
3	3.75	5.00	5.4	4.2
4	.91	1.98	2.2	1.7
6	1.67	1.48	7.4	3.9
7	.61	1.30	1.1	1.0
8	4.14	6.13	6.1	3.9
9	1.86	6.34	1.9	1.4
10	7.57	9.47	5.3	3.5
11	.90	2.70	2.8	2.2
21	1.75	2.19	8.5	5.3
23	.78	1.01	2.0	1.5
26	1.54	1.53	3.5	2.1
		DOUGLAS-FIR		
5	.34	2.31	.3	.4
12	2.63	3.79	4.9	3.2
13	1.68	2.34	.5	.5
14	1.68	2.75	4.0	3.2
15a	2.39	3.86	2.4	1.8
15b	1.18	2.83	1.5	1.3
16	1.55	2.84	3.1	1.9
17	.87	2.16	3.4	2.4
18	.84	2.59	1.0	1.0
20	2.88	2.48	7.6	4.4
22	1.12	1.37	2.6	1.9
24	1.52	2.43	3.0	1.4
25	0	1.11	0	0

[1]Depths were determined from measurements on photographs except for plot 24 which was determined by a visual estimate.

Figure 5.--Sporadic flaming typified the 15-ton-per-acre plots; this was probably caused by the relatively small amount of fuel available and the clumpiness of particles.

Discontinuity of fuel and heat flux.--Deviations were highest for the lowest values of packing ratio and fuel loading (table 5). This was especially true for the ponderosa pine plots. A discontinuity in the arrangement of fuel particles and a corresponding decline in the supply of heat for preignition could have existed because of the spacing between fuel particles. The spacing was greater in the least compact fuels: the branching habit and manner of needle growth created various sized gaps between particles, even though the slash was distributed uniformly during construction of the plots (fig. 2). Some gaps were probably so large that a substantial propagating heat flux was required to ignite unburned particles. In contrast, the mathematical spread model was developed primarily using fuel beds having evenly spaced particles without any large gaps between them.

Deviations for the plots having the highest loadings were less, possibly because the higher fire intensities furnished ample heat flux for a nearly uniform rate of particle ignitions. Fires in the low loading plots generally burned more sporadically because particle ignitions were not occurring at a uniform rate (fig. 5).

On one of the low loading Douglas-fir plots (no needles present) fire would not sustain itself; on another similar plot, fire spread was barely sustained. The amount of fuel, particle size, and particle spacing were the dominant limiting factors. The spread model contains mathematically continuous functions that are defined by scant data at the limiting end of the fire scale.

Table 5.--*Percent deviations for the observed and predicted spread rates segregated by species, loading, and packing ratio values*

Loading tons/acre	Packing ratio	Deviation	
		Percent	Average percent
	PONDEROSA PINE		
15	0.014	169	205
15	.012	241	
15	.021	117	158
15	.019	200	
15	.034	113	72
15	.040	30	
Average		145	
30	.016	71	60
30	.015	48	
30	.027	33	29
30	.026	25	
30	.041	11	12
30	.049	25	
25	.043	1	
Average		34	
	DOUGLAS-FIR		
15	.019	62	
15	.019	140	95
15	.027	83	
15	.038	39	206
15	.032	579	
15	.041	[1]/ --	
15	.048	22	22
Average		154	
30	.035	44	54
30	.031	64	
30	.040	148	178
30	.039	208	
30	.047	14	37
30	.047	60	
Average		90	

[1]Omitted because no observed rate of spread resulted in an infinite percent deviation.

Moisture of extinction.--Rate of spread is directly proportional to the moisture damping coefficient (η_m), which enters the mathematical model as a multiplier of reaction intensity.

$$\eta_m = 1 - 2.59 \frac{(M_f)}{M_x} + 5.11 \frac{(M_f)^2}{M_x} - 3.52 \frac{(M_f)^3}{M_x} \quad (4)$$

where:

M_f = moisture content of fuel, fraction of dry weight

M_x = moisture of extinction, fraction of dry weight

The moisture of extinction is the moisture content of fuel at which fire cannot sustain itself. Criteria for choosing M_x are not well established; thus use of this function in the model is rather subjective. We used an M_x of 0.24. Working backwards through the model using fuel inputs and measured rates of spread for each plot, we found that an average M_x of 0.11 for the ponderosa pine and 0.13 for Douglas-fir would have provided perfect agreement between observed and predicted spread rates. M_x values that permitted perfect agreement ranged from 0.065 to 0.45 for all plots. There is good reason to suspect that an M_x of 0.24 is too high for the fuels tested. If so, this would account for much of the deviations between observed and predicted spread rates.

A comparison of M_x with packing ratio and loading values suggests that a relationship exists between M_x and these fuel properties. In this study, plots with higher loadings developed more intense fires. The M_x would be expected to increase at higher intensities because more energy is available for preheating fuel to ignition. Plots having lower packing ratios (more porous) had greater percent deviations between observed and predicted spread rates. Apparently this was in part caused by discontinuities in fuel and heat flux. Discontinuities should tend to lower M_x.

Surface area influence.--Weighting the input variables, especially σ, by the amount of surface area in each particle size class possibly leads to overprediction of spread rate. The thinnest fuel particles in a fuel complex receive heavy weighting for their influence on fire spread rate. This seems appropriate, but perhaps too much weighting is received. Further study should refine the accuracy of this function in the model.

Regression Analysis for Fire Spread

A step wise multiple regression analysis using the combined data for both species of slash resulted in the following equation:

$$Y = 0.109(X_1) + 2.01(X_2) + 0.00827(X_3) - 1.96(X_4) \quad (5)$$

where:

Y = rate of spread, ft./min.

X_1= surface area of fuel 0 to 1 cm. in diameter per square foot of ground, dimensionless

X_2= total fuel loading, lb./ft.^{2}

X_3= windspeed ft./min.

X_4= bulk density of fuel, lb./ft.^{3}

R^2= 0.71

Standard error of estimate (0.05 confidence level) = 1.04

Surface area of the 0- to 1-cm. fuel accounted for differences between species. Presence of needles on the ponderosa pine branches provided this species with the most surface area. Of the correlation between the X and Y variables, X_1 was closest to Y ($r = 0.57$). Moisture content was nonsignificant in the regression because of the small range in moisture values. X_1 was nonsignificant in regressions in which species were kept separate.

Reaction Intensity

The measured I_R values were mostly less than the predicted ones, as shown in the following tabulation:

	Ponderosa pine	*Douglas-fir*	*Species combined*
Average reaction intensity			
Measured, B.t.u./ft.^{2}-min.	4,621	3,599	4,130
Predicted, B.t.u./ft.^{2}-min.	4,800	3,808	4,324
Average absolute deviation, percent[1]	53.6	52.8	53.2
Overpredictions	10	9	19
Underpredictions	3	4	7

We could not substantiate conclusions about the accuracy of the model to predict I_R because we were unable to measure I_R precisely under field conditions. There was a tendency to overestimate flame depth used to calculate I_R (equation 3) because the widest portion of the flame was outlined on the photographs. The fact that fuel weight loss during passage of the flame front was based on an average value for all plots also contributed to the deviations.

Weight Loss Related to Particle Size

The average percent weight loss during passage of the flame front for sample fuel particles from all plots is tabulated below:

	Ponderosa pine *Percent*	*Douglas-fir* *Percent*
Needles	[2] 96	--
Branches by diameter[3] (cm.)		
0.2	--	[4] 94 ± 2
0.5	--	80 ± 16
1	73 ± 13	71 ± 18
1-3	42 ± 21	36 ± 15
3-5	15 ± 7	11 ± 6

[1]Measured I_R - predicted I_R / Measured I_R × 100 was calculated for each plot and averaged with sign ignored.

[2]The needles were completely consumed; however, needles contain 4 percent ash which theoretically is not a weight loss.

[3]Diameters were chosen to provide sensitivity at the small sizes. Inasmuch as ponderosa pine and Douglas-fir branches have a different size distribution, different diameters for the small sizes were chosen.

[4]The second values are standard deviations. For ponderosa pine particles, n = 26; for Douglas-fir particles, n = 18.

The percent of total fuel weight loss accounted for by needles and branchwood in the different particle size classes is shown in the following tabulation:[5]

	Ponderosa pine	*Douglas-fir*
	(percent)	(percent)
Needles	44	--
Branchwood by diameters (cm.)		
0-0.5	--	19
0.5-1	11	25
1-3	37	43
3-5	8	13

Percentages for individual plots did not vary significantly for different loadings or bulk densities.

When the above percentages were determined, we knew the percent weight loss of individual particles and the proportion of the total fuel contributed by the various size classes. Fuel less than 1 cm. in diameter accounted for half of the total weight loss even though this size material was less than 30 percent of the total loading (table 1). Fuel greater than 3 cm. in diameter provided only about 10 percent of the total weight loss in the flame front (fig. 6). No change in diameter was observed for particles of this size.

For slash and other fuels containing a similar mixture of particle sizes, our findings indicate that only the fine fuel components, essentially particles less than 3 cm. (about 1 inch in diameter) supply the energy that characterizes propagation of the spreading flame front. A generalization of this statement for all fuels likely would be incorrect. Different proportions of fine fuels probably correspond to different diameter limits for the component contributing most of the energy to the propagating flame.

The percent weight loss of particles is compared in figure 7 with the effective heating number of the mathematical model defined in equation 1.[6] The effective heating number is a function of particle size; it expresses the percent of a particle that is heated to ignition ahead of the fire. In figure 7, the percent weight loss curve is drawn through points that represent particle size and the average percent weight loss in the propagating flame front for the sample particles.

The relation between the two curves, each representing a different variable, was expected and supports the concept expressed by the effective heating number. The two curves are close together at the very small particle sizes because the small particles are heated throughout at ignition and their entire organic mass rapidly converted to heat energy. As particle size increases, up to some point, the amount of a particle required for heating to ignition (ε) becomes less than the amount converted to heat in the flame (η). The effective heating number only involves that part of the particle that receives heat during the time when the particle surface rises to ignition temperature. Weight loss in the flame front, which takes place primarily after ignition, is characterized by rapid heat transfer and combustion, and thus involves a larger proportion of the particle. The percent weight loss (on an ash-free basis) should always exceed the effective heating number for the same particle sizes.

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[5]The percentages are averages based on all plots.

Figure 6.--After the flame front passed here, the fire was extinguished with a fog nozzle. Most of the remaining branchwood was over 1 cm. in diameter. About 80 percent of the branchwood less than 1 cm. in diameter was transformed into heat energy.

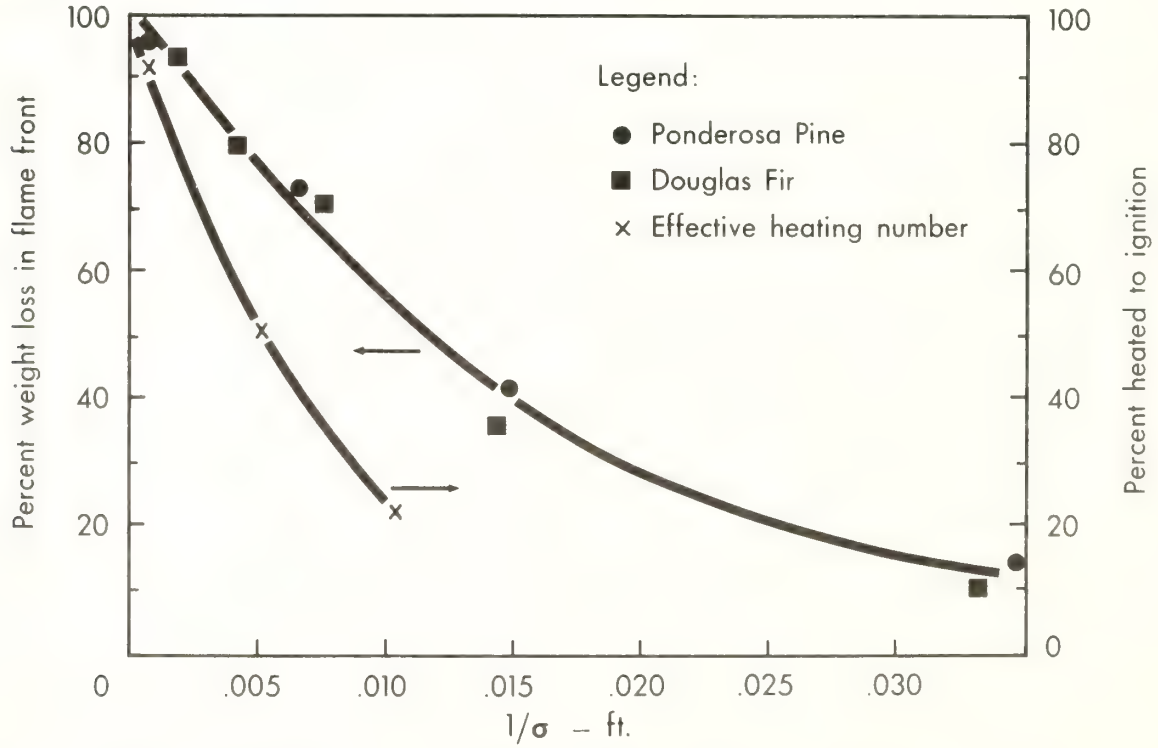

Figure 7.--Percent weight loss in the flame front and percent heated to ignition as a function of the particle surface area-to-volume ratio.

Flame Length

The relationship between flame length and certain fuel properties was examined using a stepwise multiple regression analysis. The fuel properties that varied substantially from plot to plot served as the independent variables. The following equation resulted using data from all plots:

$$Y = 4.28(X_1) + 0.00151(X_2) - 2.92$$

where:

Y = flame length, ft.

X_1 = total loading, lb./ft.^{2}

X_2 = average particle surface area-to-volume ratio weighted by fuel surface area in each size class, ft.$^{-1}$

$R^2 = 0.60$

Standard error of estimate (0.05 confidence level) = 1.52

The packing ratio was nonsignificant as an independent variable. Flame length was expected to correlate with packing ratio because (1) flame length relates closely to rate of energy release (Rothermel and Anderson 1966; Thomas 1963), and (2) packing ratio is quite sensitive to rate of energy release for the smaller size fuels in the spread model. If data covering a greater range of packing ratios had been acquired, it probably would have been significant in the regression analysis. However, loading of fine fuel (certainly particles less than 2 to 3 cm. in diameter) appears to be by far the most important physical property relating to flame length.

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[6]W. H. Frandsen. The effective heating of fuel particles ahead of a spreading fire. USDA Forest Serv., Intermountain Forest and Range Exp. Station, Ogden, Utah. (Manuscript in preparation.)

CONCLUSIONS

The mathematical model's predictions correlated reasonably close to observed rates of spread, although the model tended to overestimate. The study showed that M_x, discontinuities, and possibly the method of weighting by surface area in the mathematical model need additional study. The M_x appears to be a function of particle size, loading, and packing ratio. Its functional relationships in living fuels probably involve other properties as well. Weighting the input parameters by surface area in each size class seems appropriate for heterogeneous fuels. However, the contribution of the very fine fuels to spread rate may be overemphasized.

Although imprecise field methods prevented extensive analysis of I_R and related flame length, refinement of Rothermel's model should improve their prediction. Continued development of mathematical models for fire spread and intensity should be pursued because they will provide a sounder basis for quantitative fuel appraisal.

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The Effect Of Two Flame Retardants On Particulate And Residue Production

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ABSTRACT

The benefits from fire use — including hazard reduction, silvicultural manipulation, pathogen control, and nutrient recycling — might be forfeited by public reaction to smoke, whether harmful or not. Generally, the public desires alternatives to burning, but might accept fire if direct control of emissions were possible. The effects of diammonium phosphate (DAP) and ammonium sulfate (AS) on particulate emission and fire intensity were investigated. Particulate emission rate and total quantity were increased by DAP to several times those produced from the control. Inversely, very little increase was observed for AS. Since burning rate for AS-treated fuels was also decreased, this retardant might be useful in smoke control through extension of burning periods.

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The Effect Of Two Flame Retardants On Particulate And Residue Production

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FOREWORD

Pressure and criticism currently are mounting against open burning of forest debris in the West because of particulate emissions and their visual impact. This controversy has sparked much speculation and some research on alternatives to burning, including better utilization and mechanical treatment of slash. Because fire might be a requirement for future productivity of the site, it might be important to look at the characteristics of fire itself; specifically, in this study particulate production rates and total amount of particulate.

Emissions from slash fires include water vapor, gases, and particulate. The particulate includes both char particles and tar droplets. Several variables are involved in the description of particulate emissions: Time and rate of production, total quantity, size distribution, tar composition, and color. Emissions during the smoldering phases of the fire pose a problem in areas of nighttime down-canyon winds and early morning inversions. On the other hand, if atmospheric conditions are stable during the initial stages of the fire, production rate might become the critical factor. Because the size of the particle determines its settling rate, this variable is important under some conditions. Moreover, the fraction of tar in the particulate becomes important when considering the ramifications of smoke emissions, because it might be related to health problems.

Effects of Flame Retardants

Generally speaking, flame retardants decrease the maximum rate of combustion and increase the production of char, which is a portion of the airborne particulate from wood fires. Another source of particulate is probably the tar fractions. A retardant that enhances char and tar production will produce more particulate if it does not in some way also enhance the more complete combustion of the char by glowing. Past work has shown that most flame retardants increase CO, CO_2, and H_2O produced from the pyrolysis of wood and cellulosic fuels.[1]

The pyrolysis and combustion of cellulosic fuels can be graphically expressed as involving two competitive pathways. The low energy pathway, which occurs at temperatures around 270° C. or less for cellulose, produces char and relatively large amounts of water and carbon dioxide. The char usually sustains glowing combustion. The high energy pathway, which occurs at 340° C. or higher for cellulose, produces flammable volatiles; these support flaming combustion and produce little char or residue.

The effect of most pyrolytic flame retardants is to emphasize the low energy pathway at the expense of flaming. This is generally characterized by the lowering of the temperature of pyrolysis and an increase in char. The enhancement of the "glowing" mechanism at the expense of "flaming" does not mean there will be a decrease in residue following the fire. There may be a relative increase in energy released by way of the low energy pathway, but the total energy released may be decreased because of the residue produced. Whether the residue sustains glowing or not depends upon the chemical composition of the retardant used and the environmental conditions. This is not readily apparent if one considers only pyrolysis. When combustion is included, the picture becomes complicated by the possibility of a retardant catalyzing the glowing combustion of the residue as compared to another equally effective retardant that might alter some other combustion phenomenon.

[1] *F. Shafizadeh. Pyrolysis and combustion of cellulosic materials. P. 419-474, in: Advances in Carbohydrate Chemistry. R. Stuart Tipson, Ed., Vol. 23. New York and London: Academic Press. 1968.*

Retardants and Smoke Production

Laboratory studies have shown that some retardants, such as diammonium phosphate (DAP), apparently polymerize the tars.[2] These polymerized tars might lead to the increase in smoke. For example, Eickner and Schaffer[3] found that the most effective fire retardant chemicals, DAP and $ZnC\ell_2$, greatly increased smoke production in tests on Douglas-fir plywood. Other chemicals tested showed a decrease in smoke density. They also found that chemicals previously suspected of promoting postglowing reactions, such as sodium dichromate and ammonium sulfate, also reduced smoke index values. Similar results using particle board were reported by Syska.[4]

Diammonium Phosphate and Ammonium Sulfate

The flame retarding effects of DAP and ammonium sulfate (AS) on rate of spread and intensity for wood and fine fuel fires have been tested under controlled conditions.[5] Findings show DAP to be most effective in slowing spread and reducing intensity. Two other differences between DAP and AS are apparent. The residue remaining after the tests is always much less from the AS treatment. For example, the residue from AS treated excelsior fuel usually is close to nonexistent (fig. 1). The other difference is the tremendous amount of black smoke produced by DAP treatment as compared to the much smaller amount of whitish smoke produced by the AS treatment.

[2] *Thermogravimetric data on file at the Northern Forest Fire Laboratory, Missoula, Montana.*

[3] *H. W. Eickner and E. L. Schaffer. Fire-retardant effects of individual chemicals on Douglas-fir plywood. Fire Technol. 3: 90-104, illus. 1967.*

[4] *Arthur D. Syska. Exploratory investigation of fire-retardant treatments for particle board. USDA Forest Serv. Res. Note FPL-0201, 32 p. 1969.*

[5] *Charles W. George and Aylmer D. Blakely. Effects of ammonium sulfate and ammonium phosphate on flammability. USDA Forest Serv., Intermountain Forest and Range Exp. Station, Ogden, Utah (in preparation).*

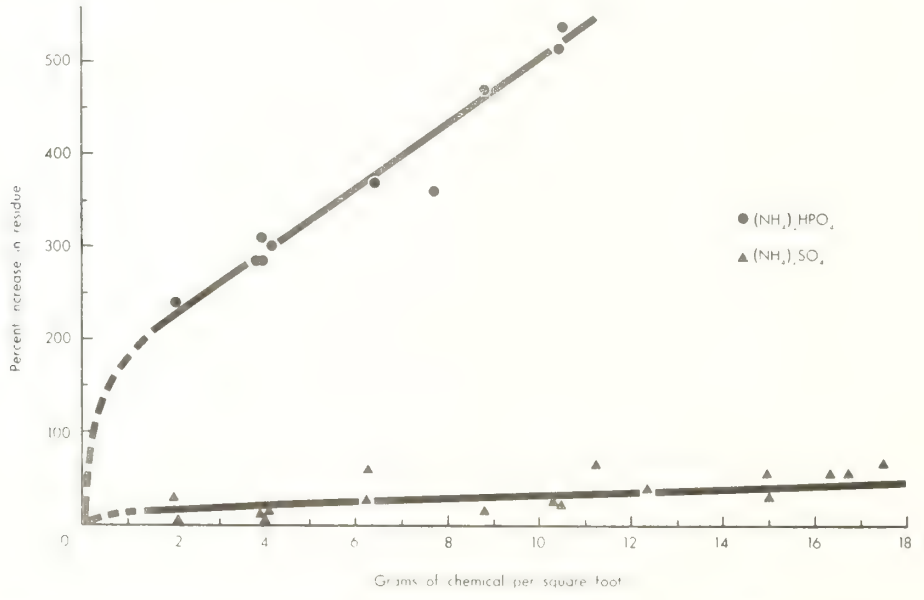

Figure 1. — The relationship between residue from spreading excelsior fires and treatment level.

EXPERIMENTAL DESIGN

The Fuel Cribs

This study was conducted under controlled laboratory conditions using a standard fuel crib, which meant we could control the various environmental and fuel factors and their influence on particulate production and energy-release rate. The cribs were conditioned to a known moisture content and chemical treatment was accurately computed. The flow and volume characteristics of the effluent gases were measured and the total convection column accurately subsampled isokinetically. This type of control is difficult to achieve under field conditions.

The cribs were constructed using about 20 pounds (9 kg.) of 3/4- by 3/4-inch (1.9-cm.) ponderosa pine (*Pinus ponderosa*) sticks, 24-3/4 inches (62.9 cm.) long. These were nailed together with 1-1/4-inch (3.2-cm.) wire brads in a configuration that would insure good combustion and allow insertion of five 24-inch (61-cm.) Douglas-fir (*Pseudotsuga menziesii*) 4 by 4's (10.2 cm. by 10.2 cm.). The average dry weight of a crib and 4 by 4's, excluding nails, was 44.0 lbs. (20.0 kg.) (tables 1A and 1B). Inasmuch as each crib had a basal area of 4.25 $ft.^2$ (0.39m^2 and a loading of 10.4 lb. $ft.^{-2}$ (50.8 kg. m^{-2}), they were equivalent to 227 tons $acre^{-1}$ (508,000 kg. $hectare^{-1}$). The approximate heat content of each crib was 8,500 B.t.u. $lb.^{-1}$ (4,722 cal. $g.^{-1}$) or 3.74 by 10^5 B.t.u. (9.42 by 10^7 cal.).

The 4 by 4's were conditioned in a sealed cabinet maintained at 90° F. (32.2° C.) and a relative humidity of 91 percent. The humidity was held constant by the use of saturated potassium nitrate solutions. Three sample 4 by 4's from different areas of the conditioning cabinet were weighed daily and sampled for actual moisture content.

The cribs were conditioned in a room maintained at 78° F. (25.6° C.) and approximately 30 percent relative humidity; the latter was maintained using a mechanical humidifier. The cribs were weighed daily and moisture contents were determined from sticks identical to those used to build the cribs.

Treatment

A calibrated spray apparatus was used to apply 10, 20, 30, or 40 percent solutions of each chemical to the cribs and the 4 by 4's. The preweighed fuel was placed on a dolly and run back and forth under the sprayer until completely coated with retardant. The highest treatment levels were achieved by alternating several hours of drying with spraying. The exact amount of chemical added was calculated after each crib and 4 by 4 reached a constant weight in their respective conditioning area (table 1).

Table 1. — The weight, moisture content, and chemical treatments of the cribs

Crib weights (grams)			Percent chemical		Percent moisture		
Stick size			Stick size		Stick size		
4 in.	¾ in.	Total	4 in.	¾ in.	4 in.	¾ in.	Total
			Untreated				
10,737	9,098	19,835	16.3	5.8	*	*	*
10,509	8,908	19,417	20.2	6.8	*	*	*
9,938	8,585	18,523	20.2	6.8	*	*	*
10,480	8,699	19,179	15.3	5.5	*	*	*
			Diammonium Phosphate Treated				
10,092	9,102	19,194	19.4	6.8	0.0	0.7	0.4
10,645	9,069	19,723	13.9	6.2	.2	.7	.4
11,964	8,853	20,822	15.3	5.5	.1	1.0	.5
9,996	9,011	19,007	19.3	6.3	.5	1.3	.9
10,762	9,101	19,953	15.7	5.7	.8	2.3	1.4
11,215	9,526	20,741	16.0	5.9	2.4	3.1	2.7
10,268	8,856	19,142	20.0	6.6	1.7	5.6	3.5
10,345	8,861	19,206	16.3	5.6	1.3	5.6	3.3
11,464	9,677	21,141	16.1	6.2	2.3	7.6	4.7
11,629	9,007	20,706	16.0	5.9	.7	8.4	4.0
10,925	9,112	20,037	15.8	6.0	1.5	9.9	5.3
11,026	8,528	19,554	17.0	5.3	2.4	14.8	7.8
			Ammonium Sulfate Treated				
11,303	8,915	21,218	15.5	5.3	.1	.5	.2
11,020	8,692	19,712	13.6	5.9	.2	1.0	.5
11,388	8,668	20,056	13.7	6.1	.3	1.1	.7
11,238	9,376	20,614	17.0	4.7	1.7	1.2	1.5
10,290	9,093	19,179	16.9	5.9	.4	1.9	1.1
10,845	9,284	20,129	15.7	5.3	.4	2.6	1.4
10,005	9,360	19,365	15.6	5.8	.7	3.4	2.2
10,576	9,270	20,026	16.3	6.3	1.8	4.9	3.0
10,783	9,302	20,085	16.9	5.7	.6	5.6	2.9
12,224	9,289	21,513	16.8	6.0	.6	6.8	3.3
11,646	8,823	20,469	15.8	5.9	1.7	8.3	4.5
10,877	10,077	20,954	16.8	6.4	2.2	8.9	5.4
11,037	8,847	19,884	18.1	6.6	2.1	11.3	6.2
11,136	9,129	20,265	16.7	4.3	1.8	11.9	6.6

Burning Procedures

The cribs were burned on a table placed on a weighing system similar to that described by George and Blakely[6] (fig. 2). Two methods were used to control temperature buildup around the load cells. A layer of Zonolite insulation 3 inches (7.6 cm.) deep was placed between the fuel and the weighing system. This material was found to be thermally stable up to 1,500°C. (2,700°F.); it is not hygroscopic. Streams of compressed air were continuously directed around the load cells during the tests as a further safeguard against temperature changes that could cause electronic drift.

The procedure for burning began by conditioning the combustion chamber to a temperature of 90° F. (32.2° C.) and a relative humidity of 20 percent. A slight positive pressure was maintained to insure removal of all of the effluent through the stack. The induced convection had no measurable effect on the burning characteristics of the fires. The test cribs, including the 4 by 4's, were placed on the weighing system and ignited at time zero using 100 ml. of a 50:50 mixture of ethanol and acetone contained in two trays. During the following 60 minutes, weight loss and radiant flux from the flame zone were continuously recorded and flame heights were photographed at 1-minute intervals. A Gier and Dunkle directional radiometer with a 15°-view angle placed 20 feet (6.1 m.) from the fire was used to measure radiant flux.

After the fire went out, the residues from the 4 by 4's and the cribs were collected and the dry weight calculated.

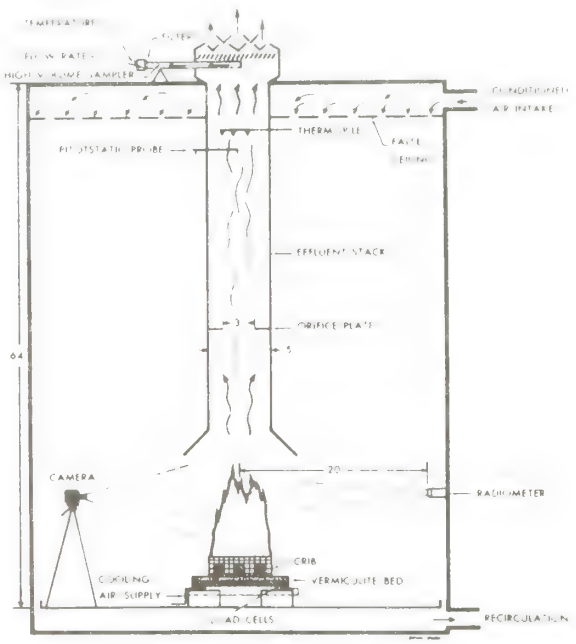

Figure 2. — A schematic representation of the combustion facilities. (Note: not drawn to scale.)

Particulate Sampling

The particulate sampling system consisted of a Neucleonic Corporation of America Model HAS 69 high volume sampler and Gelmen type A glass filter paper. The sampler was connected to a piece of pipe 4 inches (10 cm.) in diameter; this was placed (as shown at top of figure 2) in the center of the effluent stack approximately 50 feet above the fire. The end of the pipe was sealed and four holes were drilled on the underside. The holes decreased in size from the center of the stack outward so that the effluent cross section could be sampled equally.

The flow rate through the sampler was found to be temperature dependent. Therefore, gas temperature was measured and recorded at the sampler during a run. Calibration curves were used to obtain actual flow rate. The flow rate up the stack was determined using a United Sensor and Control Corporation Model PAE-36-M-W pitostatic probe

[6] *Charles W. George and Aylmer D. Blakely. Energy release rates in fire retardant evaluation. Fire Technol. 6: 203-210, illus. 1970.*

with an electrical readout. The temperature of the stack gases was measured using a chromel alumel thermopile. Data from the pitostatic probe and the thermopile were used to give stack flow rate as a function of time. This information, along with the sampling rate, allowed us to determine what percentage of the total effluent from the fire was being subsampled at any given time.

Filter papers were dried and preweighed before a test fire. A filter paper was placed in the particulate sampler; upon ignition, the sampler was turned on and flow rate and time were recorded. These readings were recorded at intervals corresponding to a drop in flow rate of 1 $ft.^3 min.^{-1}$ or 5 minutes, whichever occurred first. A given filter paper was changed when the indicated flow rate was reduced to 5 $ft.^3 min.^{-1}$ (0.142 $m.^3 min.^{-1}$). The changes involved a standard 1-minute shutdown time. This procedure was continued for 60 minutes.

Contaminated filters were dried and weighed to obtain particulate deposited during the time the filter was in place. Sample flow rate was corrected to standard conditions and then corrected to experimental conditions. The average flow rate and the total flow between readings were then computed. The sums of the flows for each filter were divided into the particulate accumulated on the filter to give particulate density ($mg.m.^{-3}$) as a function of time. The densities between filters were interpolated from the adjacent filter data. The rate of particulate emitted and the total particulate produced by the fire were obtained by relating the data from the sampler back to stack conditions.

The approximate tar content of the particulate was determined by extraction of filter paper subsamples using tetrahydrofuran. The elemental phosphorus content of the particulate from the DAP treated samples was determined using acid digestion and colorimetry. Water soluble sulfate present in the particulate was determined turbidimetrically using Sulfaver, a product of Hach Chemical Company, Ames, Iowa.[7]

The data were statistically analyzed using Program SCRAP (6.0.003) on an IBM 1620 computer.

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[7] *Norman A. Huey. Determination of sulfate in atmospheric particulate: turbidimetric barium sulfate method. P. 11-14, in: Selected Methods for the Measurement of Air Pollutants. R. A. Raft, Ed. USDHEW Public Health Serv., Cincinnati, Ohio. 1965.*

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Treatment Effect on Thermal Variables

The effect of the retardants on the burning characteristics of the crib fires is quite apparent. Both AS and DAP lowered the maximum weight loss rate, flame height, and radiant energy output. The effect of DAP treatment level on weight loss rate is shown in figure 3 and that for AS level is shown in figure 4. As can be seen, the increase in treatment level lowers the weight loss rate and increases the time to reach maximum intensity. Treatment level refers to the percent of chemical on the cribs, excluding the 4 by 4's. The graphs of the equations for treatment against maximum radiation are shown in figures 5 and 6. The DAP treatments are most effective in both cases. The difference between types of chemicals is significant at the 99 percent level as determined by the F test (table 2).

The sequential photographs in figure 7 clearly show the effects of the two chemicals on intensity: buildup time is increased and the intensity is decreased (indicated by flame size); DAP was the most effective. Figure 8 shows the three fires at the time of maximum intensity and the residue left following active combustion.

Effect on Residue

The residue remaining following the fire was related to the type of treatment (fig. 9). The total residue and DAP treatment level had a correlation coefficient R^2 of 0.87; the R^2 for AS was 0.21. However, the effects of the two types of treatment were statistically different at the 99 percent level. The residue from the 4 by 4's alone was found not to be significant, both within and between types of treatments.

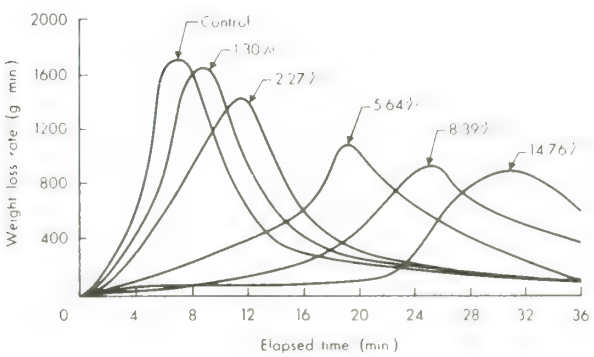

Figure 3. — Weight loss rates relative to time for several levels of DAP treatment.

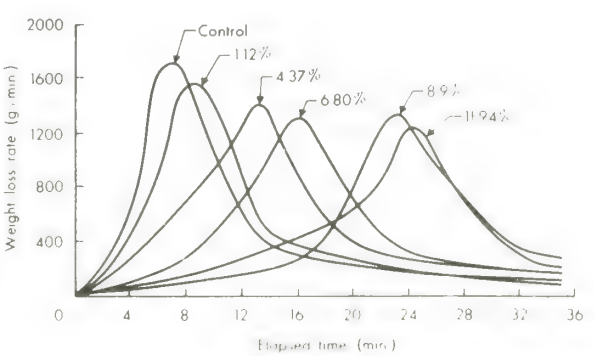

Figure 4. — Weight loss rates relative to time for several levels of AS treatment.

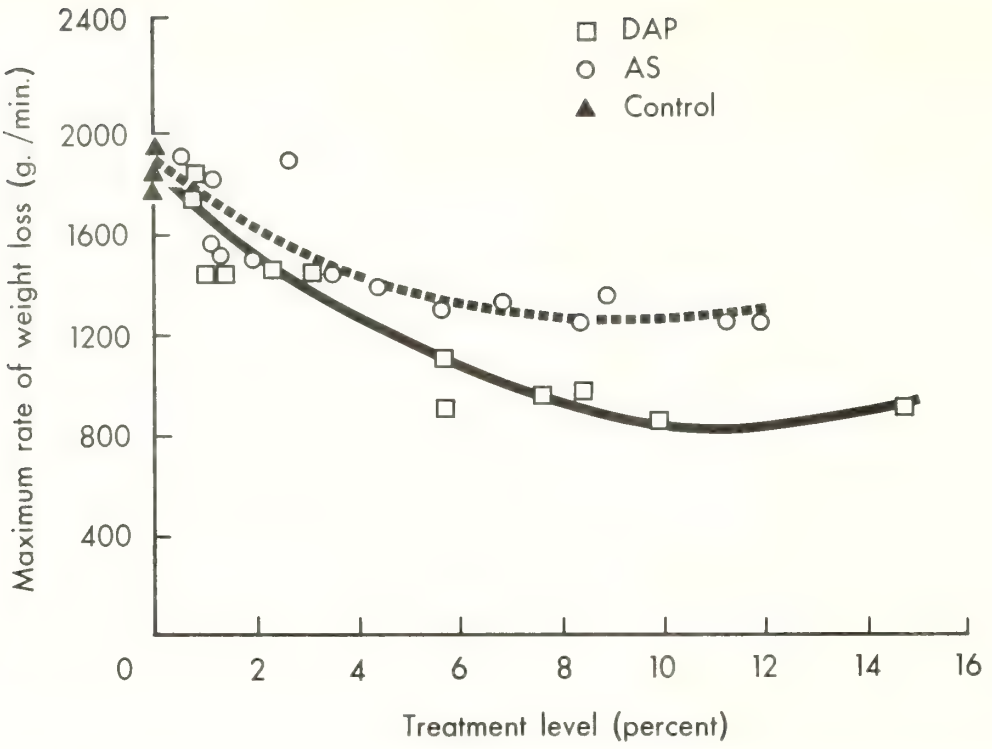

Figure 5. — The relationship between maximum weight loss rate and treatment level.

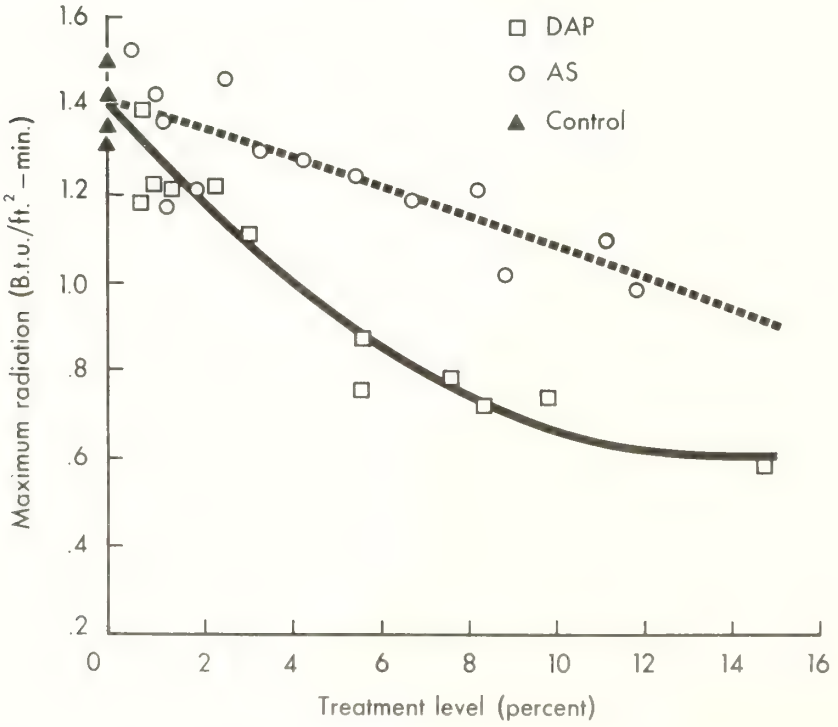

Figure 6. — The relationship between maximum radiant flux and treatment level.

Table 2. — Regression analysis and statistical significance of various test fire parameters

Parameters	Treatment	N	Equation	R^2	F	Significance
						Percent
Treatment level versus maximum weight loss rate	DAP	16	$Y=1.833-183.4x+8.27x^2$	0.94		
	AS	18	$Y=1.840-123.1x+6.39x^2$	.76		
	Pooled	34	$Y=1.828-139.8x+6.19x^2$	.76	10.01 (F=3,28)	99
Treatment level versus maximum flame height	DAP	16	$Y=10.55-.9143x+.0391x^2$	.84		
	AS	18	$Y=10.62-.4601x+.0089x^2$	.79		
	Pooled	34	$Y=10.60-.6778x+.0240x^2$	.75	4.10 (F=3,28)	95
Treatment level versus maximum radiation	DAP	16	$Y=1.382-.1148x+.0041x^2$	.95		
	AS	18	$Y=1.402-.0304x-.0304x^2$	.69		
	Pooled	34	$Y=1.388-.0638x+.0013x^2$	.65	23.50 (F=3,28)	99
Treatment level versus crib residue	DAP	17	$Y=2.495-.576x$	.87		
	AS	19	$Y=2.179+.105x$	.21		
	Pooled	36	$Y=2.258+.345+$	.42	40.42 (F=2,32: improvement)	99
Treatment level versus 4 by 4 crib	DAP	17	$Y=11.42-5.392x$	<.01		
	AS	19	$Y=12.55-.110x$	.01		
	Pooled	36	$Y=12.00-8.071x$	.01	3.46 (F=2,32: improvement)	N.S.
Treatment level versus total particulate	DAP	11	$Y=53.36+59.55x-.715x^2$	.98		
	AS	12	$Y=41.83+3.83x-.216x^2$	.36		
	Pooled	23	$Y=83.08+.706x+1.97x^2$	.32	231.00 (F=3, 17)	99
Treatment level versus maximum particulate rate	DAP	11	$Y=6.148+4.953x-.123x^2$	.88		
	AS	12	$Y=2.611+.487x-.035x^2$	.36		
	Pooled	23	$Y=7.077+.451x+.095x^2$	.22	63.00 (F=3,17)	99

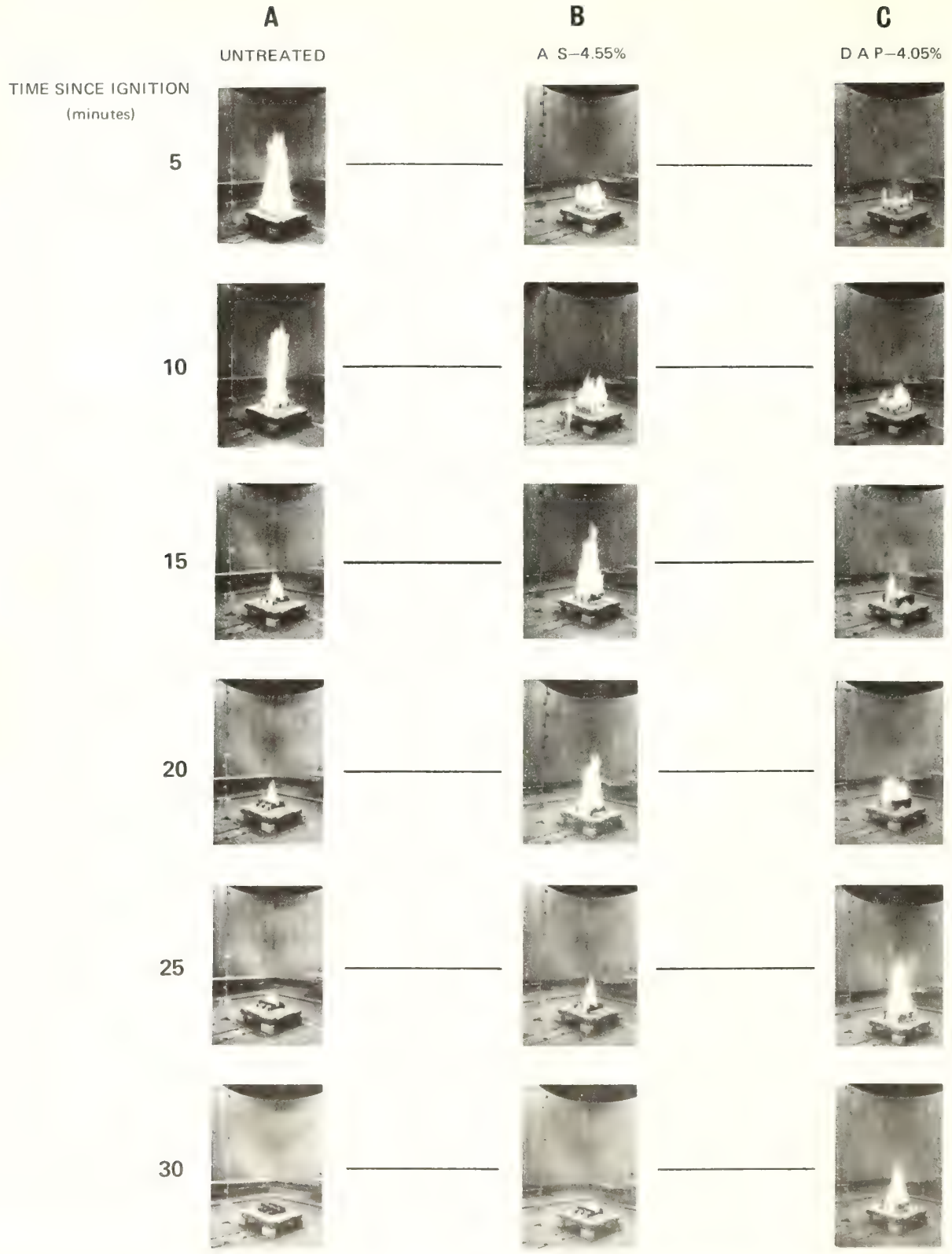

Figure 7. — Sequential photographs showing the burning of: A, An untreated crib; B, a crib treated with 4.55 percent AS; and C, a crib treated with 4.05 percent DAP.

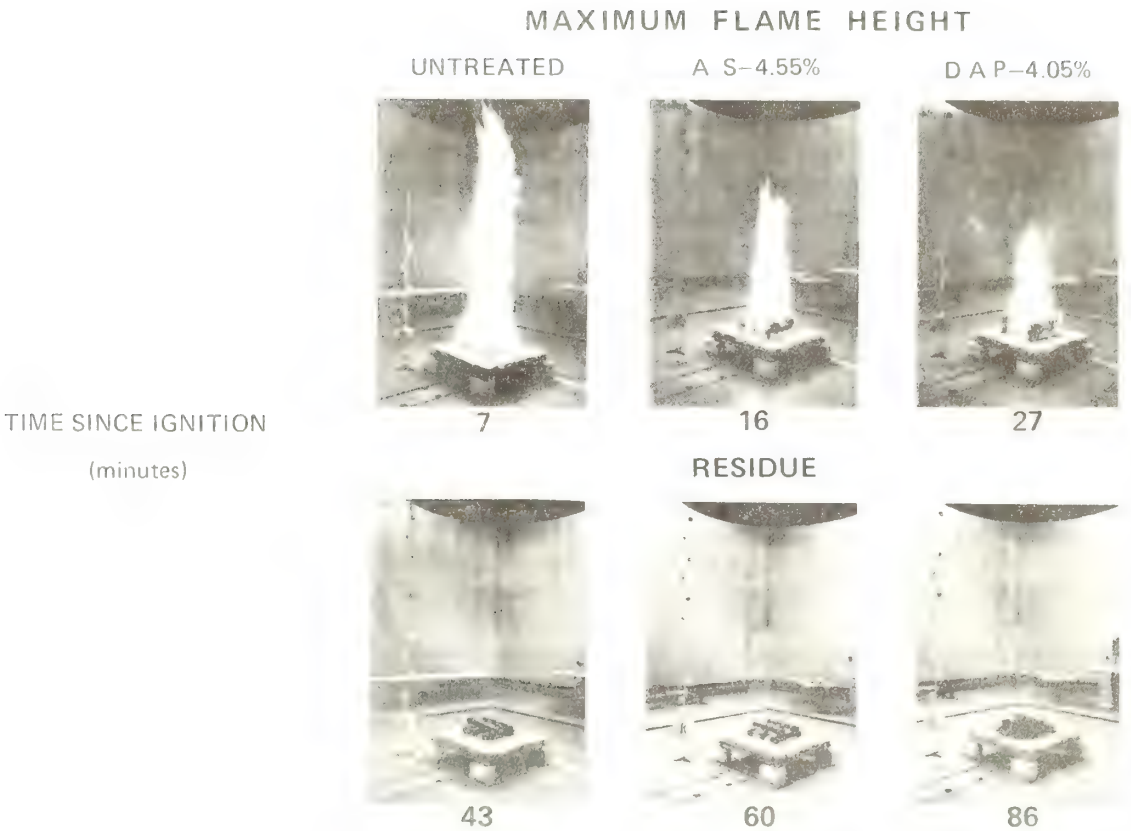

Figure 8. — Photographs of: A, Untreated crib; B, a crib treated with 4.55 percent AS; and C, a crib treated with 4.05 percent DAP, showing maximum flame height and time of occurrence and residue following active combustion.

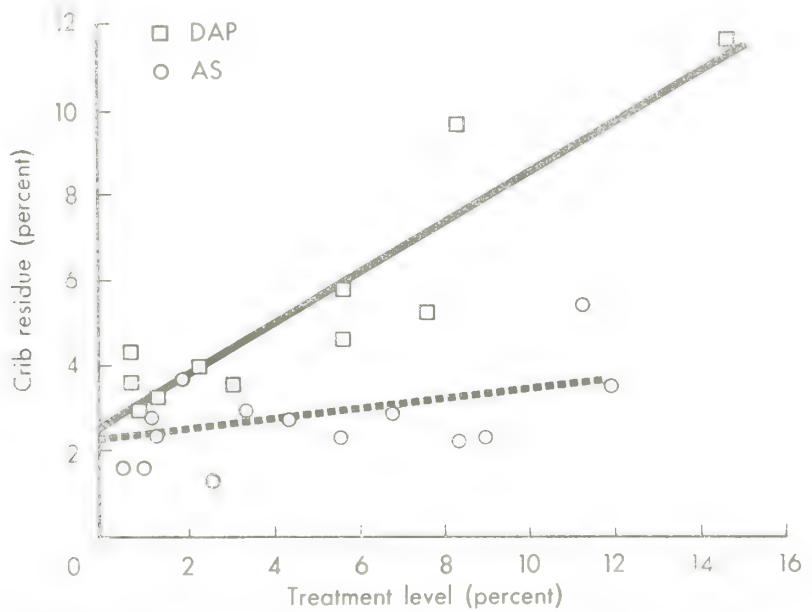

Figure 9. — The relationship between crib residue and treatment level.

Effect on Particulate

The relationship between weight loss rate strikingly different between the two chemicals. Figure 10 presents the total accumulated particulate produced from several fires. Obviously, the AS treatment had little effect on particulate production, while DAP produced substantial increases in particulate; about 20 times more than that produced by the untreated at the 14.8 percent treatment level. The rate of particulate is increased and the peak rate occurs further from the point of ignition as the amount of DAP increases (fig. 11). The range of particulate produced per unit of weight consumed was 8 to 94 $lb.ton^{-1}$ for DAP, 3.8 to 7.2 $lb.ton^{-1}$ for AS, and about 5.5 $lb.ton^{-1}$ for the controls, as shown in table 1.

The relationship between weight loss rate and particulate production rate is clearly shown in figures 12 and 13. As can be seen, intensity is decreased by both chemicals. However, there is little change in particulate production by AS.

The range in tetrahydrofuran soluble tar was 41 to 56 percent (dry weight of total particulate) for DAP treatment, 15 to 58 percent for AS treatment, and 40 percent for controls. The amount of tar was apparently directly correlated with DAP treatment and inversely correlated with AS treatment level. The phosphorus content of the DAP particulate was 11 to 17 percent, depending on treatment level. Preliminary estimates show that about 30 percent of the phosphorus added by treatment is emitted by the fire and can be collected with the particulate.

The particulate matter from the AS treated fires was found to contain 33 to 57 percent sulfate, depending on treatment level. However, this did not amount to over 10 percent of the sulfate added by treatment at the highest level.

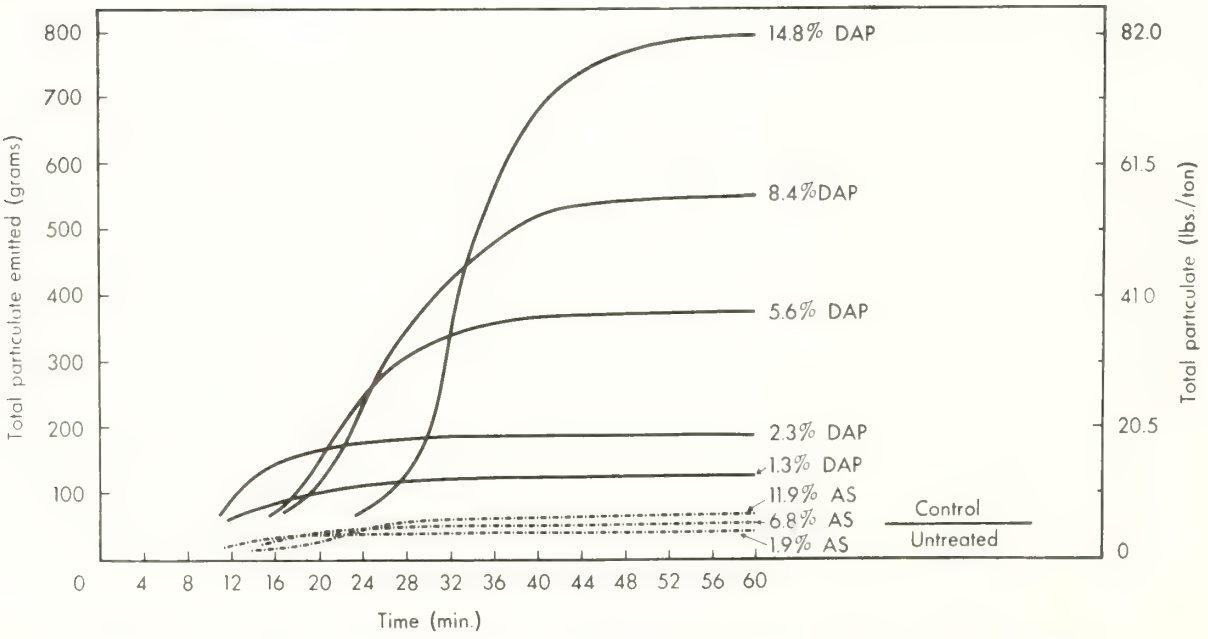

Figure 10. — The total particulate produced from fires at several treatment levels.

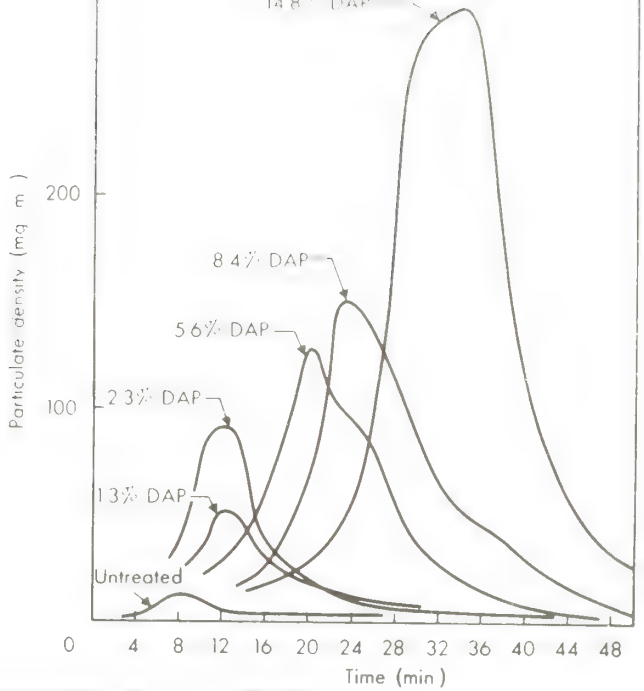

Figure 11. — The production rate of particulate relative to time for various levels of DAP treatment.

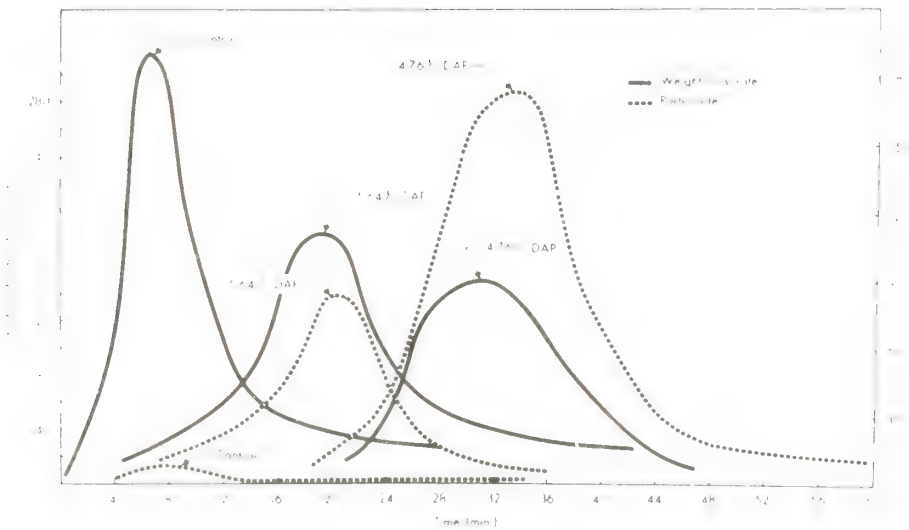

Figure 12. — Weight loss rate and particulate production rate relative to time for three DAP treatment levels and the control.

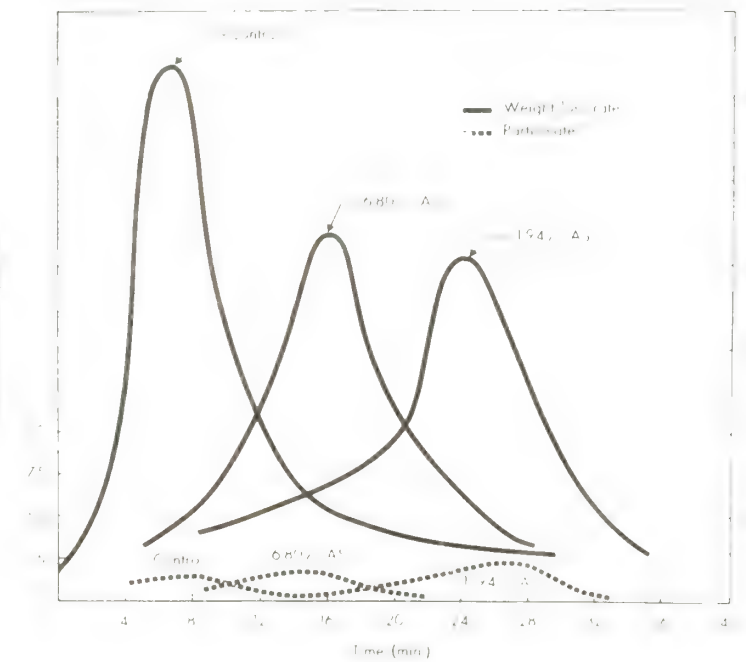

Figure 13. — Weight loss rate and particulate production rate relative to time for three AS treatment levels and the control.

DISCUSSION AND CONCLUSIONS

Two flame retarding chemicals, DAP and AS, reduced the intensity of large wood crib fires. The DAP treatments were somewhat more effective. However, DAP greatly increased particulate production. The AS treatments had much less effect on particulate formation. Total organic residue was increased by DAP treatment; it amounted to as much as 14 percent original organic weight.

As conditions for slash burning are presently dictated from a control standpoint, it is being done at low intensities and at times when weather conditions are not conducive to minimum air pollution. This burning results in large amounts of smoke, poor fuel consumption, and public displeasure. It might be possible to control intensity during the drier months, keep smoke production down, and insure more complete combustion by chemically treating the slash. Obviously, DAP would not do the job.

This study supports the possibility that DAP does polymerize the tars and make them more thermally stable. If these tars become less available to combustion, they will add to the particulate in the effluent. Apparently, a large amount of the phosphate ends up as some form of phosphorus in the particulate. The question of why AS and DAP act differently in particulate formation might partially be answered by continued study of the effects of phosphate on the tars.

Future research starting with determination of the difference in retarding mechanisms (and therefore in particulate and residue pro duction) between AS and DAP could lead to the development of chemicals that catalyze glowing to the point of practically no flaming or effluent.

The importance of fire in the forest is becoming more evident every day. Perhaps future research and land management personnel should be directed more toward fire controls rather than to "alternatives to fire."

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

GREAT BASIN STATION

—Sixty Years of Progress in Range and Watershed Research

Wendell M. Keck

AUG 24
TECH. & AGR. DIV.

USDA Forest Service Research Paper INT-118, 1972
INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

ABOUT THE AUTHOR

Dr. Wendell M. Keck was publications editor at Intermountain Station for 12 years prior to retirement in 1969. During his editorship he became familiar with the Great Basin Station's physical features and the long, interesting history of important research done there. He gratefully acknowledges technical assistance in preparing this manuscript, particularly from Dr. William A. Laycock, A. Perry Plummer, Dr. James P. Blaisdell, and former Station Director Joseph F. Pechanec.

COVER PHOTO: Entrance to Great Basin Experimental Range headquarters.

USDA Forest Service
Research Paper INT-118
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Robert W. Harris, Director

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ABSTRACT

Narrates briefly the history of the Great Basin Experimental Range from its establishment in 1912 as the Utah Experiment Station. Describes key problems in management of watershed and rangelands and the experiments devised to solve them, and indicates how results of this research have been applied in practice.

BEGINNINGS AND ESTABLISHMENT

Figure 1. — Original gate to Utah Experiment Station, 1914.

The Great Basin Experiment Station has been the headquarters for research on ecology and management of watershed and rangelands, as well as on problems of silviculture, ever since its creation in 1912 by administrative decision of Forester Henry S. Graves. The headquarters unit is located in an aspen grove on the west front of the high Wasatch Plateau in Sanpete County in central Utah at an elevation of 8,850 feet. The area of concern has always been broad. Station personnel have investigated and found solutions to special land use problems over a large part of the Great Basin and adjacent upper Colorado River Basin in Utah and Wyoming. The main field laboratory has been in Ephraim Canyon and adjacent drainages on the east side of the Wasatch Plateau. Applications of findings have been used widely in the West.

The Station has had several official names. It was first called the Utah Experiment Station (fig. 1). This name was changed to Great Basin Experiment Station in 1918 to end confusion with the name of the Experiment Station of the Utah Agricultural College at Logan. Each of these Stations had been receiving mail addressed to the other. This change of name was justified additionally by being more accurately descriptive of the extensive area the Great Basin Experiment Station served, which was far beyond the boundaries of Utah.[1]

When the Intermountain Forest and Range Experiment Station was established on July 1, 1930, the Great Basin Experiment Station became a branch of it and was officially designated as the Great Basin Branch Station. C. L. Forsling, the Director of the Station, had proposed that the name of the unit be changed instead to the Wasatch Plateau Branch on the bases that (1) the Intermountain Station would absorb the old Experiment Station,

[1] *The Great Basin Province designated by the U. S. Geological Survey includes most of the western half of Utah, nearly all of Nevada, California east of the summit of the Sierra Nevada, a large area in southeastern Oregon, and smaller portions of southeastern Idaho and southwestern Wyoming. Its 210,000 square miles include mountains, deserts, dry old lakebeds, a number of gradually receding lakes, of which the Great Salt Lake is best known, and innumerable fertile valleys and plains areas.*

and (2) the work of this branch would, he thought, relate almost entirely to the high plateau regions, chiefly summer range of Utah. But Messrs. Clapp and Chapline, respectively Assistant Forester and Senior Inspector in Charge of Grazing Research, contended that the name Great Basin was well established after nearly 20 years' use and prevailed for retention of that part of the name. Validity of their judgment was amply confirmed because the continuing research at Great Basin Station has been concerned with environment far beyond the high plateau regions in Utah.

From Great Basin Branch Station, the name was changed to Great Basin Research Center; later still it became Great Basin Experimental Range, by which it is now officially known. Despite all these official changes in name, "Great Basin Station" popularly prevails and consequently is the name used throughout this history.

The impetus for establishing the Great Basin Station stemmed at least partially from numerous requests received by the Secretary of Agriculture by 1900 for scientific study of summertime floods that originated on mountain watersheds and were seriously damaging farms and rural communities in the West. Such floods, usually of mud and rocks, were especially severe and frequent in valley communities below the Wasatch Plateau in Sanpete and Emery Counties. As late as September 4, 1913, the Ephraim "Enterprise" headlined a front-page story "Flood Pays Annual Visit of Destruction." Dr. James T. Jardine, Inspector of Grazing for the U. S. Forest Service, energetically pushed for a western experiment station, and there had been plans for a station in the Blue Mountains of Oregon. The compelling reason for establishing the Utah Experiment Station was rooted in the precarious relation of many valley communities to the mountainside watersheds above them. Ephraim Canyon sustained several severe floods between 1889 and 1910. Manti Canyon, just a few miles south of it, flooded many times between 1888 and 1902. Following creation of the Manti Forest Reserve[2] in 1903, Manti Canyon was closed to grazing for several years, and no serious flood has come from it since 1902. An official report in the spring of 1910 attributed flooding in nearby canyons in 1909 to prolonged overgrazing. Reynolds (1911) reported a destructive flood in Ephraim on September 10, 1910, that left a thick layer of mud on the streets and filled irrigation ditches, culverts, cellars, and basements with debris. Grainfields west of the city were also damaged. So the need for determining the causes of summertime floods and for devising effective means of preventing or controlling them was compellingly evident.

■ Experimental Range Created

Since the problems of wildland management are varied, research has required use of numerous individual sites where certain specific characteristics of soil, terrain, climate, and vegetal cover were typical. A specific area for research in the drainage where the headquarters is located was long considered and used but was never officially designated until recently. On April 28, 1970, the Great Basin Experimental Range, comprised of 4,608 acres in Ephraim Canyon drainage, was formally set aside for range and watershed research by executive order signed by A. W. Greeley, Associate Chief of the Forest Service. The Great Basin Experimental Range is all within the Ephraim Ranger District of the Manti-LaSal National Forest and is chiefly in Ephraim Canyon. It occupies parts of 17 sections of Township 17 South, Range 4 East, Salt Lake Base and Meridian.

Although not large, this is an important piece of real estate. Additional acreage can be added to this experimental range as may be required. The present area will serve for future intensified research as well as for demonstrating the usefulness of findings.

The western boundary of Great Basin Experimental Range lies along the Manti-LaSal National Forest boundary and is at about 6,800 feet elevation. From there the northern boundary of the Experimental Range rises

[2] *An Act of Congress approved March 4, 1907, changed the name "Forest Reserve" to "National Forest."*

rather steadily to an elevation of about 10,300 feet at the Skyline Drive. This 3,500-foot rise occurs within a distance of about 4.5 airline miles, but some 10 miles by the Ephraim-Orangeville road. In traversing the Range, this road rises from the lower edge of Merriam's Transition life zone through the Canadian and Hudsonian zones to the Arctic-Alpine zone. Total annual precipitation increases from an average of 16 inches at Major's Flat (7,100 feet elevation) to about 40 inches at the summit. These four life zones and associated biotic communities, so close together and easily accessible, provide great diversity in plant species, soils, and climate, and thus give opportunity for convenient, efficient study of a wide variety of ecologically oriented problems of wildland management.

Site Selection and Buildings

The Utah Experiment Station literally had to be carved out of the wilderness. First-time visitors to the headquarters invariably ask: "How did this beautiful site happen to be selected?" Accounts of the actual selection vary. One states that about 1911 A. E. Sherman (District Forester), Homer Fenn (Assistant District Forester), R. V. R. Reynolds (Forest Examiner), and a Mr. Hodson of the Manti National Forest set out to select a possible site for an experiment station. These four men and the narrator, A. W. Jensen, first supervisor of the Manti National Forest, drove up Fairview Canyon in a buggy to look at a site in the approximate location of the present Gooseberry Ranger Station, but they decided against it. They then drove up Ephraim Canyon to the area now called Bluebell Flat, but rejected it, as they did another proposed site farther up the canyon. As they were returning down the canyon, they turned off the road at the point where the Station is now situated and were immediately and favorably impressed with the site. James T. Jardine, then Chief of Experiment Stations in the Department of Agriculture, and Dr. A. W. Sampson, who was Chief Investigator of Range for the Department, concurred that the site selected was good.

Once the headquarters site had been selected and boundaries for the Station area had been determined, trees had to be felled, stumps pulled (fig. 2), land leveled, fences installed (to protect Station grounds and some experimental areas from being overrun by stock), and buildings constructed. Hence it is no surprise that Director Sampson's first annual report (December, 1913) of the Station's

Figure 2. — Clearing ground on west side of laboratory building, June 1914.

work devoted more than 20 pages to describing improvements already made and explaining additional improvements needed for the immediate future.

First construction was the Director's residence (now called the East House), a laboratory building, the Assistants' residence (fig. 3), and a barn. All these buildings except the Assistants' residence, which burned in 1935, are still standing and in good condition. The Assistants' residence was replaced in 1936 on the same site by an attractive dwelling now called The Lodge (fig. 4). It was a Civilian Conservation Corps (CCC) construction project and displays much excellent workmanship, including rooms attractively finished with knotty pine paneling. In time the need for a barn passed, and since 1955 the building has been a toolshed.

To promote varied studies in revegetation, a 17- by 40-foot greenhouse was built back of the office-laboratory building in 1913. It was divided into cold-bed and hot-bed compartments with separate heating and ventilating systems. The need for a greenhouse passed, and in 1933 the building was adapted for use as a dwelling for summer assistants and other temporary employees.

As scope of the Station's work broadened, more scientists and helpers were employed; this required building additional living quarters. A garage with dormitory facilities on the second story was built in the late 1920's. Summer employees nicknamed this structure "The Palmer House" after the famous Chicago hostelry. In 1933, in the early days of the CCC, two additional houses were built. The residence now called the End House was a few yards southwest of the Assistants' residences. The South House, originally designated as a dormitory, was built directly opposite the office-laboratory building and faces it. For many years the South House has been the locale for numerous training sessions and other meetings. Both the End and South Houses have two stories; the second floors have dormitory facilities.

After erection of these two buildings the Station headquarters area was landscaped in 1934 (fig. 5). An oval driveway lined with stones loops inside the area enclosed by the residence and office buildings. The flagpole was moved to the center of the oval, and the weather station was moved from the yard in front of the office-laboratory building to a convenient spot in the grass and shrub testing

Figure 3. — Main buildings, Great Basin Experiment Station, 1924. The Assistants' residence (left) burned in 1935 and was replaced by the Lodge in 1936.

Figure 4. — The Lodge at Great Basin Experimental Range, built in 1936. At extreme right is the west end of the original greenhouse, which was converted into a dwelling for summer assistants.

Figure 5. — Great Basin Branch Station yard after landscaping in 1934. Foreground area was later planted to trees and shrubs; center area now has native grasses, forbs, and shrubs.

area back of the End House. A picket fence and row of trees that had bounded the lawn in front of the first three houses were removed.

Water for the Station came from a large spring on the face of the cliff southeast of the residences. Since the spring is in a bed of limestone, the water was — and still is — very hard. Dr. Sampson recommended building a cistern to supply soft drinking and culinary water, but this was never done.

To keep horses within a convenient distance, a 50-foot corral was fenced off near the barn. Numerous other fences were built around the headquarters area and around smaller areas, such as the grass and shrub testing area, for protection against wandering stock (fig. 6). These fences were uniformly the rail-and-tie type, commonly called "log-and-block" fence. For the most part, these were built of aspen logs 16 feet long with a minimum diameter of 6 inches; ties were 30 inches long and 8 to 12 inches in diameter. Aspen suitable for this construction was plentiful and was chiefly used, but logs of conifer species were often intermixed. Many logs have had to be replaced, but the fences are still generally sturdy and effectively protect the Station from grazing by bands of sheep in the summer.

■ First Projects and Personnel

When the Utah Experiment Station was established, its number one task was to discover the causes of destructive summertime floods that originated on mountain watersheds; closely related, of course, was expectation that discovery of causes would suggest possible and feasible means for preventing them. Analysis of the watershed problem quickly revealed that problems of grazing and range management were inextricably related to it.

The initial research program at Utah Experiment Station included nine projects. Director Sampson's annual report of the Station for 1913 discussed them under the general headings of Grazing and Silviculture.

A study preliminary to the research on erosion included measurements of soil and air temperatures and of precipitation and soil moisture at three elevations throughout the

Figure 6. — A section of the aspen log fence that surrounds Great Basin Experimental Range and some smaller areas within it.

growing season. The highest weather station was at 10,000 feet, probably at or near the site of the present Alpine Station; the next lower one was at the Experiment Station headquarters at 8,850 feet; and the third was about 1,700 feet lower, near the present National Forest boundary at Major's Flat. These locations gave data for the Hudsonian zone (spruce-fir association), Canadian zone (aspen association), and Transition zone (oakbrush-aspen association). The records of temperatures, precipitation, and soil moisture, plus observations of the condition of vegetation, gave bases for measurement of the length of the growing season in the three life zones. They showed that the growing period in the Transition zone is about 3 weeks longer than that for the Canadian zone, and about 6 weeks longer than the growing season in the Hudsonian zone. Within 6 miles by wagon road, a scientist could encounter 6 weeks' difference in length of growing season.

Historical importance of the Great Basin Station can hardly be measured solely in terms of the numerous experiments performed there and their results, significant though they be. The Station has been a training ground for many men who later achieved prominent positions in the Forest Service and other governmental and academic positions. As long ago as 1939, Lincoln Ellison remarked in a talk at the Utah State Agricultural College:

> *Great Basin may be regarded as one of the two cradles of range research in this country. The other is Jornada Range Reserve in New Mexico. It is said that almost everybody in range research has, at one time or other, worked on the Jornada, and almost the same may be said of the Great Basin.*

He named A. W. Sampson and F. S. Baker, who were then teaching at the University of California; W. R. Chapline, who had become Chief of Range Research for the Forest Service, and C. L. Forsling, who became head of the Division of Forest Research in Washington, D. C.; and C. F. Korstian, president of the Society of American Foresters and for many years dean of the School of Forestry at Duke University.

In an age that takes for granted the employment of numerous full-time personnel to staff any research organization, a reader is considerably surprised — if, indeed, not mildly shocked — to examine the personnel phase of the work at Utah Experiment Station. At the beginning, Director Sampson apparently was the only yearlong employee. In his annual report for 1913, he wrote:

> *During the active field season there were three temporary assistants and one permanent assistant. The temporary men were Messrs. William R. Chapline, Jr., who now has a permanent appointment in the Forest Service as Grazing Assistant, Richard O. Cromwell, and Paul H. Roberts.*

He commented that Mr. Chapline's services began on June 1 and ended on November 15. The other two temporary assistants worked only short terms in the summer field season. F. T. McLean, who had been Forest Assistant on the Manti Forest prior to establishment of the Utah Experiment Station, was the "permanent" assistant until October 20, when he went on furlough. E. R. Hodson, also from the Manti Forest, succeeded him.

In the very first years, Mr. McLean was responsible for much of the experimental work in silviculture. His work was considerably augmented a few years later by that of F. S. Baker and C. F. Korstian, who were probing the mystery of the "pineless belt" (see Silvicultural Studies) in the brushlands of Utah and southern Idaho.

Director Sampson was favorably disposed toward using advanced forestry students as temporary summer assistants. He found them hard workers, eager to make good; they readily grasped the significance of the research and willingly accepted some hardships and long hours to promote the projects; and they could do hard manual work "quite as well as the theoretical." "For these reasons," he wrote in his first report, "I therefore strongly favor the employment of students to as great an extent as practicable in future seasons."

Prominent among the young men who worked at Utah Experiment Station in its early days was Leon H. Weyl, Grazing Assistant. He had completed his junior year in the

School of Forestry at the University of Nebraska when he was appointed Field Assistant in June 1914. Director Sampson highly praised his academic training, his rapid, accurate work, and his pleasing personality. Weyl's diaries for 1916 and 1917 record widely varied tasks: emptying precipitation tanks at Areas A and B, getting the snow stakes ready for winter measurements, working on the greenhouse roof, working on plant succession studies, taking photographs, mending the telephone lines, working on poison plant records, working on climatology computations — and many more. "Talking over work with Sampson" is a frequent entry. No wonder the Director liked young college men as workers! Mr. Weyl was coauthor with Dr. Sampson of "Range preservation and its relation to erosion control on western grazing lands" when the USDA Department Bulletin was published in 1918.

Salaries in the early days were unbelievably low. A. W. Jensen recalled, "To begin with, the rangers' salaries were $60.00 per month for the short period they worked. I succeeded in getting them raised to $75.00 before I left. They fed their own horses and received no expense money." In forecasting needs for 1916, Director Sampson listed his own salary at $2,200, plus $500 for expenses, and commented:

> *However, now that most of the construction work is well along, it is believed that the Director will be available personally to do an appreciable amount of experimentation, so that three assistants will suffice.*

Temporary assistants for the summer field season were paid $75 a month plus $25 for expenses. A permanent Grazing Assistant was to receive $1,200 per annum plus $250 for expenses.

Another facet of life for Station personnel in the early days that startles modern-day employees was the parsimony with which supplies and ordinary office conveniences were supplied. This is graphically revealed in the following memorandum, dated November 29, 1927, from Director Forsling to the Operation Office of District Four in Ogden:

> *We are now entering upon the sixth year that the Great Basin Experiment Station has had offices in the District Office in Ogden. During all of this time we have been using office tables as substitutes for desks. Upon one or more occasions last year and the year before when some equipment from the Veteran's (sic) Bureau was available I made request of Mr. Pearson or the Maintenance clerk to consider the needs of the Station for double pedestal office desks. This was taken up again by memorandum or letter this fall. No desks have been received todate (sic). I understand that the unit of the Veterans Bureau at Salt Lake City has no more surplus desks.*
>
> *At the present time it is necessary for Mr. Nelson and myself to keep papers and other material such as one will ordinarily keep in a desk tied in bundles or stacked in baskets and piled on top of a book-case unit we have. There are many other little conveniences that a double pedestal desk affords that we do not have. I think that the merits of our need are comparable with those of the average office. In all probability the headquarters of the Great Basin Station will be maintained in Ogden for a number of years and we hope permanently. I would appreciate it very much if early consideration would be given to the procurement of two double pedestal desks for use by the Great Basin Experiment Station if it is thought that procurement of such equipment for the Station is a legitimate thing for the District office to do.*

THE WATERSHED STORY

Watersheds A and B

Among the officially designated studies, "Protection, Grazing vs. Erosion" was the longest continued and is best known today. This project was designed to determine, with considerable exactness, the relation of grazing and vegetal cover to erosion. It has been described and discussed extensively in the literature of watershed research as the studies of Watersheds A and B,[3] which were first called "Erosion Areas."

The two Erosion Areas were established in 1912. Area A covers 11 acres and Area B covers nine. The two watersheds are about 900 feet apart and are at an elevation of 10,000 feet on a generally west-facing slope at the crest of the Wasatch Plateau. They are typical small watersheds in the Subalpine zone and were strategically established in an area where thousands of sheep had been trailed summer after summer, where oldtimers and valley residents averred that you could count the number of sheep bands on the mountaintop by the number of clouds of rolling dust on the horizon. Each is a complete watershed but neither one has a permanent stream. Soils on both Areas are residual clays and clay loams derived from limestone and shales. Average slope gradient of Area A is 18.5 percent; Area B's slope is 16.3 percent.

Annual precipitation averages 33 inches, but only about 4 to 6 inches come during the 3-month summer growing season; and this amount varies considerably from year to year. During most of the year, storms in this area are of low intensity; but in July and August they have a dramatically different pattern. They are brief, narrowly localized, and intense. Rainfall at the rate of 2.2 inches per hour for 20-minute periods has been recorded many times on both these watersheds, and such storms hit any given area on the Plateau at least once every few years.

Several things make these watersheds and their story outstanding. One is the length of continuous observation and study they have had. Another is the length of continuous cli-

[3] *Details of description of these two Watersheds and their treatments are from Meeuwig (1960).*

matic records for the studies — nearly 60 years by now. Vegetation has been surveyed periodically ever since 1912. Surface runoff and the resulting sediment have been measured since 1915, and summer storm intensities have been recorded since 1919. Continuous records of temperature and precipitation have been maintained on the Watersheds, at headquarters, and elsewhere on the Experimental Range. These long-term detailed records of climatic factors, of growth of vegetation, and of results of treatments applied to these two Watersheds constitute a tremendous mass of data. Interpretation of these data has had far-reaching significance, as will appear later.

The treatments of Watersheds A and B included manipulations of vegetative cover. When the studies began in 1912, vegetation on Watershed A had already been depleted to a 16-percent cover, whereas Watershed B had about 40-percent cover. This condition was maintained by carefully controlled grazing through eight growing seasons, i.e., through the summer of 1919, so as to determine the amount of surface runoff and sediment production from a severely depleted watershed as compared to runoff and erosion from a watershed having fair plant cover. During that 8-year period Watershed A produced six times as much runoff and five times as much sediment as Watershed B, which was maintained with a 40-percent cover of vegetation. Preliminary results of the study were published by Sampson and Weyl (1918).

In 1920, cover on Watershed A was allowed to recover naturally by excluding grazing; within 5 years the vegetation built up to about the same 40-percent cover that Watershed B had in the beginning (fig. 7). During this period, Watershed A produced about

Figure 7. — Eastern boundary of Watershed A, 1970. Foreground shows small area of virtually bare ground, but most of the watershed is covered by grass, forbs, and shrubs.

three times as much runoff and sediment as Watershed B. From 1924 to 1930 average plant cover on both areas was about 40 percent. Watershed A, though, continued to produce about twice as much runoff and erosion as Watershed B, largely a result of a few bare spots. Results of the first two decades of study were published in 1931. (See Forsling 1931; Stewart and Forsling 1931).

From 1946 through 1951, vegetal cover on Watershed B was depleted to 16 percent by heavy grazing, and the watershed became a potential flood source. During this period Watershed B produced more than four times as much runoff and 12 times as much sediment as Watershed A. Late in 1952, Watershed B was artificially treated by disking, installing contour furrows on steeper slopes, and seeding a mixture of adapted grasses and some forbs. This restorative treatment completely transformed Watershed B. The disking and furrowing broke up the gully system that had formed when cover was sparse, and by 1954 an excellent stand of grass had become established over most of the area. Two major results of this artificial restoration of Watershed B have been: no summer storm runoff since 1953; and improvement of vegetal cover from a sparse stand of low-value broadleaf herbs to a good stand of palatable grasses. Sediment production on both Watersheds now is negligible.

Progress of the experiments on Watersheds A and B was not as smooth as the preceding narration may suggest. Director Sampson's report for 1913 recounted several annoying delays. For one thing, road conditions owing to abnormal summer rainfall were such that hauling a loaded wagon up Ephraim Canyon could be accomplished only at long intervals. Sand and cement for the bases of the steel sediment catchment basins for the two Watersheds had to be hauled from Ephraim, more than 10 miles away and approximately 5,000 feet lower. The first sediment catchment basins were made from sheet steel and provided with weirs. They were roughly 12 feet long, 5 feet wide, and 5 feet deep. Director Sampson had assumed that these basins would be large enough to allow the sediment in the water caught on each watershed to settle sufficiently to get a measure of the total silt. But he was in for a bad time. On September 1, 1913, just after the sediment basin on Area A was installed, 0.17 inch of rain fell within a very few minutes. The tank filled in approximately 2 minutes after the full stream reached it, but the water kept pouring in for another 15 minutes; he reported, "It would have taken at least eight tanks to have held the water and silt which passed over the weir in Erosion Area A." Another shower 2 days later further demonstrated the inadequate size of the tank; so substantially larger concrete sediment catchment tanks for both Areas were built in 1914 (fig. 8).

It is difficult for the uninitiated to visualize what the sediment catchment tanks revealed until reading a statement by Director Sampson written in 1919.

> *Seeing, of course, is believing, but if anyone had told me that as much as a car load, or approximately 50,000 pounds of air dry dirt and rock would be deposited from a ten acre area from a single storm I would probably be inclined to ask permission to examine the figures for myself. Nevertheless air dry sediment of from 20,000 to 50,000 pounds has been deposited several times during the six years from a single rainstorm.*

Figure 8. — Concrete sediment catchment tanks built at [illegible] Area A in 1914.

With such volumes of erosion occurring year after year, it is no wonder that the range on the crest of the Wasatch Plateau was seriously depleted, that areas of bare rock appeared frequently, or that floods to the valley had been growing progressively more destructive.

The studies on Watersheds A and B have shown conclusively that summer floods are a direct result of reducing plant cover below minimum amounts required to prevent excessive runoff from high-intensity summer storms. Where vegetal cover has been severely depleted, it is often necessary to resort to contour trenching and seeding to restore satisfactory watershed conditions. Because of the success of this early work, few persons in valley towns today can remember any destructive summer flood roaring down from the mountaintop.

Little active watershed research is currently being carried out at the Great Basin Station. A few climatic stations and rain gages still collect records of physical factors, and the sediment basins and weirs on Watersheds A and B are being maintained. These records will provide the necessary background for any future watershed work that may be done on the area.

Infiltrometer Research

The treatments applied to Watersheds A and B produced significant information about the cause-and-effect relations of vegetative cover to storm runoff and soil erosion. However, Sampson and others recognized that treating instrumented watersheds was not the only useful way to study problems of the hydrology of rangelands. Several investigations at the Great Basin Station used rainfall-simulating infiltrometers, devices to apply artificial "rain" to plots at predetermined rates. Water and soil washed from the plots are collected and the amounts of water retained by the soil are calculated. In this way the hydrologic effects of a wide range of soil and vegetative cover conditions can be studied, as well as their effects on runoff and erosion from different intensities and amounts of rain.

The major infiltrometer studies were conducted on an area seeded to introduced grasses in 1952 at the head of Manti Canyon and on adjacent unseeded areas. Three years after seeding there were no differences in soil stability, infiltration capacity, and soil bulk density between seeded and unseeded areas (Orr 1957). However, 7 years after seeding, differences were significant (Meeuwig 1965). The seeded areas had less capillary pore space and greater bulk density in the surface layers of soil. This indicated that, while disking and seeding effectively increased growth of forage on deteriorated subalpine ranges, these treatments should be used cautiously on areas that are in good condition because they can, at least temporarily, detrimentally affect infiltration and soil stability by reducing cover, soil organic matter, and soil porosity.

Meeuwig also found that grazing significantly affected relations between plant cover, soil, runoff, and erosion. The grazed plots had significantly less protective soil cover, less noncapillary pore space, more capiliary pore space, and more runoff and soil erosion than the ungrazed plots. Conditions needed for high water retention and soil stability under heavy rainfall were found to be one or more of the following: (1) bulk density of surface 4 inches less than 0.97, (2) protective cover of litter and vegetation at least 85%, or (3) noncapillary porosity of the surface 4 inches of soil of at least 22 percent. If all of these conditions are considered, then the protection requirements in terms of each factor become somewhat less stringent.

Shrub Plantings

A second experiment that was part of the early watershed story was a project for planting cuttings and sprouts of aspen (*Populus*

tremuloides),[4] native willow *(Salix* spp.), mountain elder (blackbead elder — *Sambucus racemosa* ssp. *pubens* var. *melanocarpa*), wild currant (*Ribes* spp.), and other promising shrubs in areas at the heads of mountain streams. The object was to determine practicability of trying to check erosion at the heads of streams and thus prevent floods at the point where they usually started.

Dr. Sampson laid out five plots at heads of three creeks and planted some 3,600 cuttings in June and July 1913 with crowbar and mattock. His report on the experiment is replete with accounts of details that should have been handled differently: dates for cutting and planting, treatment of cuttings before planting, and numerous others. Long periods of dry weather hampered growth, and snows came early that fall. Some cuttings were in poor condition when planted. Since the experimental planting plots could not be fenced, livestock trampled many cuttings. Generally, the cuttings of aspen and elder performed very poorly, but willow cuttings usually grew satisfactorily.

The report of this shrub-planting experiment closed with plans for continuing it the following year, with numerous changes in procedure. New Canyon had flooded seriously in August that year, much of the newly built road was destroyed, and many lawns in Ephraim were covered with silt and debris. So there was plenty of incentive for trying to find means of preventing further serious erosion of gullies near the heads of streams.

A report on this project at the end of 10 years[5] stated that the initial plan of planting and seeding parallel to gullies proved ineffective and that the terrace plan of planting and seeding had been resorted to. Wild currant, yellowbrush *(Chrysothamnus viscidiflorus)*, and snowberry *(Symphoricarpos oreophilus)* failed to become established; but blue foxglove *(Penstemon rydbergii)*, sweetsage *(Artemisia michauxiana)*, yarrow *(Achillea millefolium* spp. *lanulosa)*, slender wheatgrass *(Agropyron trachycaulum)*, mountain brome *(Bromus carinatus)*, bottlebrush squirreltail *(Sitanion hystrix)*, timothy *(Phleum pratense)*, smooth brome *(Bromus inermis)*, and Kentucky bluegrass *(Poa pratensis)* performed fairly well. This report stated further that considerable planting and seeding had been done on Watershed A and that the vegetative cover had improved appreciably as a result. Native turf-forming grasses were spreading well, but cultivated grasses did not produce viable seed. Plants with taproots were less satisfactory than plants with lateral-type roots. "The experiment," said the report, "has proven that erosion can be controlled by planting and protection against grazing without exorbitant cost but the treatment necessary is justified only on watersheds of very great importance."

■ Induced Snow Drifting

Early in the 1900's there had been some local interest in the possibility of "trapping" snow near the summit of the west side of the Wasatch Plateau as a means of prolonging spring snowmelt and thereby increasing the supply of water for summertime use in the valley. Many persons had observed that clumps of subalpine fir trees near the summit effectively caused drifts that persisted for 2 to 3 weeks after undrifted snow nearby had all melted (Lull and Orr 1950). In September 1947, H. W. Lull and H. K. Orr built four snow fences, each 50 feet long, in the headwaters of the Left Fork of Ephraim Creek. Measurements in the spring of 1948 showed that the 7-foot fences had been ineffective. The 11-foot fences, though only half as high as the average natural tree barriers, had produced a drift that contained about 70 percent

[4] *To avoid confusion of nomenclature, all scientific names are the current correct names as listed by Arthur H. Holmgren and James L. Reveal (Checklist of the vascular plants of the Intermountain region, USDA Forest Service Research Paper INT-32, 160 p., illus. 1966). Common names are those published in Standardized Plant Names except for a few common names in use at the time of publication.*

[5] *Grazing investigative program. (On file at Great Basin Experimental Range.) 1923.*

as much water and lasted about 70 percent as long after disappearance of undrifted snow as the drifts formed back of clumps of fir trees.

In 1957, Meeuwig continued and extended the study of inducing snowdrifts. A drift induced by a 16-foot snow fence was 15 feet deep and contained 100 cubic feet of water per lineal foot of fence whereas adjacent undrifted snow was only 8 feet deep. The induced drift persisted 10 days later into the summer than the undrifted snow, and average water content along the main axis of this drift was 13 inches. Meeuwig's results were promising, but shifts in personnel and program emphasis prevented any further work on snow drifting at the Great Basin Station. The Rocky Mountain Forest and Range Experiment Station has subsequently done considerable additional research on induced snow drifting.

THE GRAZING AND RANGE STORY

Depleted Range

Early studies at the Station had demonstrated that Ephraim Canyon's summertime floods were caused by depletion of high-elevation watersheds. Analysis of the watershed problem quickly revealed that problems of range management and grazing practice were inextricably related to it. How had this upland range come to deteriorate to such poor condition?

Settlement of the Sanpete Valley began about 1850, and the following 30 years saw a steady increase in the production of cattle and horses. Extensive and excellent summer range was available on the mountains and was free. Just as the range cattle business reached a peak about 1880, the sheep business began to take hold. Sheep were more profitable for anyone who could obtain enough summer range for them; so there began a bitter struggle between sheepmen and cattlemen. Tactics employed by both sides proved detrimental to the range, and its carrying capacity diminished rapidly. Reynolds (1911) graphically reported the outcome of the range battles:

> *The result was that, between 1888 and 1905, the Wasatch Range, from Thistle to Salina, was a vast dust bed, grazed, trampled and burned to the utmost. The timber cover was reduced, the brush thinned, the weeds and grass cropped to the roots, and such sod as existed was broken and worn. The basins at the head of the canyons suffered most, relatively, because they contained the best feed for sheep and were less broken in topography and more easily accessible. Their scanty timber cover, however, made them particularly liable to removal of the soil by wind action wherever the surface cover was broken through and the dry powdered earth exposed. These high mountain pastures, therefore, received not only the most abuse, but have been proportionately longer in recovering from its effects.*

It is no wonder that Sampson and his early colleagues found that the mountaintop range

areas suffered from two types of serious damage, both resulting from prolonged abuse of the land: valuable forage species had been killed out, and several inches of topsoil had been washed or blown away; this left an erosion pavement of comparatively unproductive soil and rock. Of these two types of damage, the loss of topsoil was the more serious because without it reestablishment of vegetation for forage and soil stabilization was difficult.

Before a decade of the sheep era had passed, the mountain range areas had been damaged so seriously that the era of summertime floods began. No serious flood had been reported from any canyon in this area prior to 1888, but serious floods occurred in Ephraim Canyon and other canyons in the area in nine seasons between 1888 and 1910. The history of flooding in other canyons along the Wasatch Front during that period was similar. Even in Castle Valley on the eastern side of the mountains, the story was the same: agricultural and business properties were destroyed and fish in the mountain streams were killed.

By the end of 1901, the situation in Sanpete County was becoming desperate. In March 1902, a large area on Manti Mountain was withdrawn from entry, and on May 29, 1903, President Roosevelt created the Manti Forest Reserve by proclamation. Less than 5 months later, the Commissioner of the Land Office ordered all sheep removed from the western slope of the mountains before the start of the following grazing season. He also ordered the supervisor of the Forest Reserve to prohibit all grazing of cattle, horses, and sheep on some 8,830 acres in the uplands of the several forks of Manti Canyon. This strict closure was in effect for five grazing seasons.

The drastic action paid off: Manti Canyon has had no serious flood since August 1902 (Reynolds 1911). Seven years later, both Ephraim and Six Mile Canyons, which had been overgrazed for 20 years after 1882, were flooded severely; but Manti Canyon was not affected. In 1909, after representations by many stockmen, the Forest Service permitted grazing in the area by cattle and horses at the rate of one head for each 30 acres, or a total of about 300 head.

Searching for Better Range Management

Temporary exclusion of stock from mountain rangelands was all very well as an emergency measure, but the Utah livestock industry could not tolerate the locking up of high-elevation summer range as a permanent arrangement; so the stockmen began to put pressure on Forest officers to permit summer grazing on National Forest lands. Forest officers were thus caught between their responsibility to care for the rangelands within their jurisdiction and their understandable concern for the welfare of the stockmen. From all the confusion and turmoil, though, one idea emerged with increasing force and clarity: better grazing management was necessary both for preservation and improvement of the rangelands and for continuation of the livestock industry.

Development of satisfactory grazing practices on public lands has been beset by numerous and varied problems. Fundamental was development of a program that would give vegetation the greatest chance to grow consistent with the profitable handling of large numbers of livestock. From the beginnings of range research, many workers have felt a strong sense of urgency. This has resulted partly from realization that millions of acres had been seriously depleted and that other millions of acres were constantly threatened; but many persons did not — and still do not — realize that depletion usually is an irreversible process; so they optimistically assumed that areas damaged by overgrazing, trampling, and erosion could eventually be restored to their original maximum productivity. But the unpleasant fact is that topsoil once lost is lost forever.

The question of "range readiness" for grazing has long been thorny. Many stockmen thought — some still do — that range was ready for grazing when new growth of grass amounted to no more than 2 or 3 inches. But study of life histories of many grasses demonstrated that these key species should have about 6 inches of new growth before stock

are permitted to graze them (Sampson and Malmsten 1926). This headstart of growth of plants was especially important because, at that time, livestock grazed the range continually once they entered. This initial growth became less important with the advent of rotation grazing schemes in which any given area of the range is grazed during only part of a grazing season, and is grazed at a different time each year. Related questions in the early studies were how long stock should be permitted to remain on range and how fully forage plants should be utilized.

James T. Jardine, Inspector of Grazing for the Forest Service, was among the first to state that the condition of animals was not in itself a safe way to judge whether a range was overstocked (Jardine 1916). In 1915 he wrote that "it had been common practice on privately owned land to put on all the livestock that the range would carry and turn them off in fair to good condition, in the belief that if they came off in satisfactory shape the range was not overstocked or injured." He commented: "This is true, provided the season of grazing is limited so as to give the vegetation a chance to do more than merely produce a few leaves, which are eaten as soon as they are long enough to crop." He admitted that this theory worked well enough on winter pastures that had been protected during their growing season, and on National Forest ranges where stock were not allowed to graze until vegetation was well along in its growing season, and on some spring-fall range. But, he concluded: "It does not work . . . where the stock are on the pasture to its apparent capacity during all or the greater part of the growing period of the main forage plants. When this is the case the number of stock must be reduced materially below the number which can be kept in good condition, if the pasture is to be kept up."

Against active opposition the Forest Service has stoutly maintained for more than half a century that the condition of plants and soils is the only sure way to judge condition of a range. Intensive studies of plant behavior and soil conditions have confirmed this stand. In discussing proper utilization, Jardine stated categorically:

> *When the season of grazing that will give the vegetation the greatest chance to grow, consistent with the profitable handling of the stock, is decided upon, then, and not until then, can the number of stock a given pasture will carry be consistently estimated. It should be determined finally by careful observation of the range, not the stock, over a period of from 3 to 5 years.*

■ Revegetation

In 1913, even though experiments had not yet demonstrated relationship between summer floods and the denuded high-elevation rangelands, many presumed some such relation existed. Furthermore, increased production of forage obviously was needed. Hence, an urgent initial problem for the Utah Experiment Station was how to rehabilitate depleted range areas if, indeed, restoration were possible. This problem seemed susceptible of two solutions: natural seeding by native species, and direct seeding with natives or exotics. Assuming that either or both of these treatments were feasible, other questions had to be answered. If rangelands could be seeded naturally, how should grazing be managed to assure maintenance of their improved condition? If direct seeding were to be resorted to, what species were best adapted to the high-elevation ranges; when should they be planted; what cultural methods should be adopted; and, assuming successful rehabilitation, how should these rangelands be managed both for their best maintenance and improvement and for providing needed forage for livestock and game?

Director Sampson believed wholeheartedly in the efficacy of permanent quadrats for studying change in vegetative cover; so he proceeded in 1913 to establish quadrats on the Two-Mile Strip in the Manti National Forest on the Wasatch Plateau (fig. 9). The Two-Mile Strip was an area 2 miles wide at the heads of canyons along the Divide on the Plateau where stock were not permitted until August 20, at which time the earlier forage plants would have

Figure 9. — Typical quadrat near the Two Mile Strip.

mature seeds. The Strip had been established about 1911 following strong urging by a committee of two sheepmen, two cattlemen, and a merchant representing the communities of Orangeville and Castledale in Emery County. This area, understandably, was in great need of improvement; hence quadrats were established here to determine to what extent the depleted lands were naturally revegetating. Some quadrats were on steep slopes; some were on comparatively level ground; some were on south-facing slopes; some on west-facing — harsh sites in either case; some were on moderately grazed areas; some on overgrazed; some on soils supporting fairly dense plant associations; others on sparse stands.

In the initial year, not much could be done beyond locating and marking the quadrats and photographing some for future comparisons. Even fencing had to be postponed until the following year. Director Sampson projected considerable expansion of this project for subsequent years, firm in the belief that the results would be used in management of depleted rangelands grazed by cattle and sheep. The very slow recovery of depleted mountain grazing lands was not yet realized; so he estimated completion of the project by 1918.

ARTIFICIAL SEEDING

Sampson recognized that natural seeding might not accomplish rehabilitation on overgrazed range adequately or quickly enough; hence his plan for experiments in direct seeding of denuded rangelands. The threefold objective was to determine which species were best adapted to local conditions, what time of the year was best for seeding, and what cultural methods should be employed.

In the autumn of 1912, two experimental areas, each with two plots, were planted to timothy, Kentucky bluegrass, orchardgrass *(Dactylis glomerata)*, and smooth brome. One

of these areas was one-half mile south of Seeley Creek Ranger Station; the other was on Philadelphia Flat. They represented typical sites in the Hudsonian zone on both sides of the summit of the Wasatch Plateau. Fairly satisfactory stands were obtained the first year for all species but orchardgrass. On the Seeley Creek area, sheep were herded over the area to trample the seed into the ground (fig. 10), but on Philadelphia Flat a mechanical harrow was used. White sweetclover *(Melilotus alba)* and red clover *(Trifolium pratense)* were also planted but did not produce satisfactorily at these high elevations.

One useful result of the first year of this experiment was learning that wherever the native "bluebell" *(Penstemon rydbergii)* grew well, one could expect a good stand of Kentucky bluegrass. Results at Seeley Creek were better than those at Philadelphia Flat because the latter was a favorite bedground for cattle. To determine the nature and extent of loss of seedlings, quadrats were established for extended observation. Also, at Seeley Creek, a small part of the range was fenced to determine how well vegetation would succeed under complete protection as compared with vegetation that was subject to annual grazing by sheep.

A related project experimented with species, most of them native, that promised to be adaptable to ranges where they did not naturally occur. The species were: white sweetclover; Idaho fescue *(Festuca idahoensis)*; showy oniongrass *(Melica spectabilis)*; bearded bluebunch wheatgrass *(Agropyron spicatum)*; biscuitroot *(Lomatium dissectum)*; clover *(Trifolium* spp.*)*; and sweetanise *(Osmorhiza occidentalis)*. Despite great care in cultivation, the seed of the fescue, biscuitroot, and sweetanise did not germinate; but the others, to quote Director Sampson, "showed good field germination, and the stand at the end of the season was as good as might be expected."

Research in range seeding continued at Great Basin Station during the 1930's and 1940's; these studies especially emphasized

Figure 10. — Sheep "harrowing" seed after broadcast sowing on open area near the head of Seeley Creek.

species adaptability, methods and season of planting, and reduction of competing vegetation. Substantial progress during this period developed suitable procedures for many large-scale projects in range revegetation and also the background for important later research. Contributions by A. Perry Plummer and Neil C. Frischknecht were especially important.

Reorganization within the U. S. Department of Agriculture resulted in transfer of certain range research projects and employees from the Forest Service to the Agricultural Research Service in January 1954. Research on range seeding for domestic livestock was continued at Great Basin Station by William J. McGinnies. Emphasis was on fertilizing and methods of planting to increase stand establishment. This work has been continued at Great Basin Station by A. T. Bleak since 1956, primarily in studies of germination of grasses and forbs under winter snow, and on winter mortality and longevity of seeded species.

Following the 1954 reorganization, the Forest Service retained research projects in range seeding that were related to protection of watersheds and improvement of big-game ranges. Research by the Forest Service prior to 1954, and that of both the Forest Service and the Agricultural Research Service after that date, formed the basis for up-to-date procedures for restoration of depleted ranges in the Western States (Plummer 1943; Bleak and Plummer 1954; Plummer and others 1955, 1959, 1968; McGinnies 1959; Bleak 1968; and many others). As a result of these investigations more than one hundred species, both exotic and native and about equally divided among grasses, forbs, and shrubs, are being successfully planted today on western ranges.

Of special importance, researchers found that merely broadcasting seeds of adapted species in depleted aspen, Gambel oak, or chokecherry stands at leaf fall resulted in productive stands of herbaceous plants. In many areas, especially on mountain ranges, association of shrubs with herbs or aspen trees resulted in as great, and often greater, production of herbaceous plants as where the shrubs and trees had been eliminated or where they did not naturally occur. This is somewhat paradoxical because on many ranges covered by more competitive plants it is necessary to reduce their competition considerably by brushland plowing, anchor chaining, or some similar technique. However, seeding these ranges to adapted species by airplane or drills in the fall or winter results in good stands. These procedures are now widely used throughout the West.

Further development and improvement of western ranges by artificial planting continues as an important part of the research program at Great Basin Station.

GAME RANGE RESTORATION RESEARCH

Much of the research at the Great Basin Station since 1955 has been in the game range restoration project sponsored cooperatively by the Utah Division of Fish and Game and the Intermountain Forest and Range Experiment Station.[6] This research has been necessarily directed toward a variety of related problems: What range areas were in critical condition? What kinds of game range could be improved? What species of grasses, forbs, and shrubs were adapted for use in restoration and improvement treatments? What techniques of land treatment and planting were effective and feasible? And a host of others. Research was directed chiefly toward restoration of winter game range, but summer range at higher elevations was also considered. The winter ranges are critical because large numbers of mule deer and elk depend on them for winter forage.

The complexity of the necessary research is suggested by the varied character of the environment. Some areas of winter range in the salt-desert shrub type receive less than 8 inches of rainfall annually, whereas precipitation on some summer ranges varies from 30 inches at lower altitudes to 60 or more inches near mountaintops. Likewise, length of the growing season varies from an average of 120 days in the oakbrush type to only 70 days in the spruce-fir

[6] *For a comprehensive account of the problems, procedures, and results of the first 13 years' work on this project, see Plummer and others (1968). For yearly reports on separate phases of this work, see the series titled "Job Completion Reports for the Game Forage Revegetation Project" issued by the Utah Division of Fish and Game (now Utah Division of Wildlife Resources) since 1956.*

type. Terrain varies from fairly flat to steep; fertility of soil also varies greatly. Most soils over the State, derived from a variety of sedimentary rocks, have a basic reaction; but soils in some game ranges, notably in the Uinta, Tushar, and Mineral Mountains, are acid. Competing vegetation (e.g., pinyon pine and juniper) makes artificial revegetation extremely difficult.

Some game range areas are covered by dense thickets of Gambel oak. Most foothill areas are favorable environment for juniper and pinyon pine trees, which choke out grass or forb understory; this type offers much opportunity for improvement. Since thousands of acres in Utah are wildlands dominated by this type and can be considerably improved for use by both game and livestock, the significance of this research can be appreciated easily.

Intensive initial trials of forbs, shrubs, and grasses, and of planting techniques have been conducted in Ephraim Canyon at elevations of 5,700 and 7,200 feet; these elevations are the lower and upper edges of big-game winter range and are also the approximate borders of the pinyon-juniper type. In addition, numerous species of grasses have been tested in plantings on the Wasatch Plateau at more than 10,000 feet. Species that show promise of adaptability have been tested further at more than 50 outlying sites scattered over the State. This research has emphasized study of shrubs and forbs because comparatively little information about these classes of plants had been developed and published, whereas the study of grasses has been extensive and the volume of available information about them is correspondingly large.

Besides studying adaptability of plant species, this cooperative project has studied means for improving efficiency of methods for reducing plant competition and for effective sytems of planting seeds, seedlings, wildings, and other materials. Chaining, cabling, burning, disking, and pipe harrowing have been tested to determine which treatment provides best site preparation for typical problem areas. For direct seeding, conventional drilling, drilling with scalpers, tractor dribbling, and broadcasting with and without covering have been tried. Seedings in autumn, winter, and spring have been compared for effectiveness.

This project has been directed by A. Perry Plummer, a career Forest Service range scientist, with active assistance from Biologists Homer Stapley, Donald R. Christensen, Stephen B. Monsen, Richard Stevens, and Bruce Guinta of the Utah Division of Wildlife Resources. Results have been substantial. Successful restoration programs have been completed on more than 120,000 acres within the State. An important feature of this project is the unusually early use of results of this research. Treatments developed by this project have been so successful that several other public land managing agencies in Utah and neighboring States have adopted them or used them with minor adaptations. Annual Job Completion Reports published by the Utah Division of Wildlife Resources report ratings of performance of more than 300 species of shrubs, forbs, and grasses (Plummer and others 1970); this is a selection that has survived from initial testing of more than 3,000 species and variants. Likewise, studies of germination, of techniques of site preparation and planting, of protection of plantings against the ravages of small mammals, and of changes of ground cover after eradication of pinyon-juniper stands are continuing.

Plant Vigor Studies

Early studies of rangeland and its management continually raised questions about plant characteristics that had never been answered. Effective planning of range management requires knowledge of plant vigor and the factors that contribute to it. The implicit question that stimulated numerous early research projects was: how intensively and how frequently can a given area (or species) be grazed but still maintain or improve the condition of the range? This question prompted the initial studies of natural revegetation of depleted areas and the studies of artificial seeding. From these developed another group called the Plant Vigor studies, which were directly related to the question stated above.

Figure 11. — General view of part of the forage nursery where early studies of plant vigor were made.

Development of desirable grazing technique requires answers to such questions as: How early can the range be grazed? How many times within a growing season can it be grazed? How completely may plants be utilized and still have the range maintained and improved?

The first plant vigor experiments were started at the Station headquarters in the autumn of 1916 (fig. 11). For one experiment, three species that had produced well and had recovered satisfactorily from grazing were studied; namely, mountain brome, smooth brome, and slender wheatgrass. The experiment was designed to determine just how different intensities and different frequencies of grazing affected the seasonlong growth and vigor of these valuable grasses. Thirty specimens of each species were planted in each of four plots. Harvesting varied from one to four times during the growing season.

Plots where herbage was removed four times during the season produced the least dry matter, and plants were seriously weakened; plots harvested twice produced the second least amount of dry matter, and plants were somewhat weakened. Plots cut just before seed maturity generally showed the greatest production of dry matter and best plant survival.

A companion project studied nine species: five grasses, three forbs, and one shrub. To obtain the most accurate data possible, the forage removed from all plots was harvested with shears "in a method simulating grazing as nearly as possible." The season and closeness of harvesting represented some 24 methods of harvest differing in date, frequency, and closeness of cutting.

In 1919 this project was expanded by planting numerous additional native forage species in the nursery. The following year, many new plots were set out on the range so that performance could be watched under actual range conditions. Some of these plots were in the oakbrush type (elevation 7,200 feet) and some in the spruce-fir type (about 10,000 feet).

These experiments and their results were reported in detail by Director Sampson and Harry E. Malmsten, Grazing Examiner, in a "landmark" publication (Sampson and Malmsten 1926). Published while the science of

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range management was literally in its infancy, this bulletin provides unusually interesting reading today for layman and scientist alike.

These early studies in plant vigor stimulated increasing interest to learn how plants responded to grazing. This, in turn, generated great interest in study of life histories of numerous range plant species and in a phenomenal collecting of specimens for herbaria at the Station, at District headquarters, and in Washington. Indeed, at one time, the Manti National Forest had the reputation of being one of the most intensely botanized Forests in the Nation.[7] Plant collections from the Experiment Station were numerous from the beginning through the 1940's and the correspondence between Lincoln Ellison and William A. Dayton and other taxonomists was voluminous. The plant collections and the resulting herbarium were very helpful in familiarizing both researchers and managers with the species on the range and their interrelationships.

When C. L. Forsling succeeded Sampson as Director of the Great Basin Station in 1922, interest in the plant vigor experiments was still running high. He believed the study should be continued but more nearly in line with actual grazing practice. Accordingly, he devised an experimental project in which sheep would graze a pasture until the forage had been utilized to a predetermined degree. Then the pasture would be allowed to recover. The grazing program was designed to match the 24 types of harvesting that had already been done with shears at the Station's forage nursery.

For this project Forsling selected a location at the head of the Cove Fork of Ferron Canyon, about 6 miles south of the Alpine Station. On a virtually level terrace about 100 feet below the present Skyline Drive and on the east side of the Divide, he laid out and fenced three contiguous 20-acre pastures (fig. 12). These were called the Cove Paddocks. The sheep-grazing experiments began in 1923 and continued through several seasons. Fieldwork here virually ceased in 1932 and the paddocks were later abandoned. Despite careful design and control of the grazing procedures and despite the fact that volumes of data were collected from several detailed reconnaissances and were elaborately analyzed, no publication about this project appeared. The slow response of mountain vegetation to treatment was still not recognized by these early researchers. If these experiments had been continued long enough, change in vegetation due to the treatments might have occurred.

■ Studies of Poisonous Plants

Presence of poisonous plants was at least a nuisance, at worst a plague on mountain rangeland.[8] Sometimes, poisonous plants fill in areas where desirable species have been killed off, especially by overgrazing. Great increase in poisonous plants is often a symptom of overgrazing. Some of these plants are unpalatable and are eaten only when animals are desperately hungry; thus they persist on ranges after associated nonpoisonous plants have been grazed out.

Since tall larkspur *(Delphinium barbeyi)* was a poisonous tall forb found most commonly on the Wasatch Plateau, Sampson designed a study to determine feasible methods for eradicating it. This plant starts growth each year from buds that sprout from the collar of the parent root; so Sampson theorized that if the aerial stems were cut at the right time — when the root contained the least stored food — it might sufficiently weaken the roots as reproductive parts so that the plant would die from lack of food and from the competition of neighboring healthy plants. Results of studies on plots Sampson established in 1913

[7] *This statement was made in a letter by W. R. Chapline, dated April 8, 1924. He stated further: "The Washington Office records indicate that the first plant collection reached here from the Manti in September, 1912, so that collecting has taken place there for at least 12 years. Altogether we have record of 27 collections on the Manti, embracing 1365 specimens . . . "*

[8] *Earl V. Storm in 1919 reported annual losses of 6,000 cattle and 16,000 sheep within National Forests due to eating poisonous plants.*

Figure 12. — Site of Cove Paddocks experiments near Skyline Drive.

near Seeley Creek Ranger Station showed that the growing plant stored its starchy food chiefly in its roots and collar. Grubbing the plants an inch or two below ground surface early in the growing season, before much food was stored, gave reasonably good control.

This study provided considerable information about food storage and the time of clipping that would produce greatest effect. Thus it furnished essential background for plant food reserve studies 20 years later by E. C. McCarty and Raymond Price (1942).

Relation of Grazing to Aspen Reproduction and Range Condition

Aspen dominates several million acres of high-elevation summer range in the Rocky Mountain and Intermountain areas, mostly between the mountain brush and subalpine conifer zones. When in good condition, the lush undergrowth in aspen furnishes considerable cover and forage for wildlife and livestock. The type also has esthetic value, some commercial value for certain timber products (e.g., excelsior), and is valuable for watershed protection. Studies on aspen here actually predated the establishment of the Great Basin Station. One study on the effect of grazing upon aspen reproduction (Sampson 1919a) was started in 1902 and dealt with management of grazing on aspen range, particularly on what effect sheep grazing had on reproduction and growth of aspen following clearcutting. The conclusions were that, to avoid destruction of aspen sprouts after cutting, three courses of action were available: (1) entire exclusion of grazing for 3 years; (2) exceedingly light grazing by sheep; or (3) moderate grazing by cattle. The height of the sprouts was found to be the main factor determining when reproduction was protected from destruction by livestock grazing. A surprisingly large proportion of aspen sprouts were killed during the first 3 years by causes other than grazing; e.g., frost, and bark consumption by gophers, mice, and rabbits. Big game populations were quite low at the time these early studies were conducted; later research elsewhere has shown that deer and other game can also browse sprouts too heavily to allow aspen reproduction. Other factors, particularly competition from herbaceous vegetation, may also suppress aspen regeneration.

Interest in aspen range continued, and some 35 years later Jack Major (now at the University of California, Davis), Walter Houston (now with the Agricultural Research Service), and Lincoln Ellison, began a study designed to help managers assess the condition of aspen range (Houston 1954; Ellison and Houston 1958). Their study was concerned primarily with openings in aspen forest rather than with the aspen stand itself. They pointed out that openings are key areas, that they have more grass and forbs than the aspen stands and consequently carry the bulk of the grazing load. If the cover in these openings is kept in good condition, understory vegetation in the tree areas will also be good. Comparison of forage production under aspen canopy and in openings can aid in judging range condition.

Houston's criteria for judging the condition of aspen range included amount of cover, species composition, amount of current aspen reproduction, current production of all types of forage, and presence or absence of erosion. In evaluating species composition he gave highest rating to species that were tall, succulent, and palatable.

ECOLOGICAL ENDEAVORS

■ Plant Studies

Late in the 1960's countless Americans began to be aware of a complex of problems loosely labeled "environment." Some could be specifically classed as "pollution," but many others eluded classification. For the first time, many heard the word "ecology," and soon, without knowing precisely what the term meant, called themselves "ecologists" — and multiplied. Many of these new ecologists of the 60's and 70's are surprised to learn that Forest Service scientists, including ecologists, have been studying plants and animals in relation to their environment ever since the Utah Experiment Station was established in 1912. Indeed, the problem of destructive summertime floods from the high Wasatch Plateau was basically an ecological problem related to depletion of vegetation by grazing animals. This in turn posed the necessity for learning much about range vegetation and its interrelations with animals, soil, climate, and other environmental characteristics. This chapter briefly describes some of these projects and evaluates their results.

In applying the principle of plant succession to range management, Sampson noted two objectives to be kept in mind; namely, that herbage should be cropped at a time in its growing season when growth and reproduction would sustain minimum injury, and that the forage crop should be used when it was most needed and when it was palatable and nutritious (Sampson 1919b). He opined that plants could be grazed closely early in the season once in 3 or 4 years without danger and advocated the deferred-and-rotation grazing system which provided for this. Judicious grazing, in his opinion, disturbed vegetation cover only slightly.

Sampson's knowledge of range plants and their characteristics was already well developed when he arrived in Utah. He used knowledge gained in previous experience, notably in Oregon, in studying the complex range problems on the Wasatch Plateau. The extent and depth of this professional background are shown well in his Department of Agriculture Bulletin No. 4, "The Reseeding of Depleted Grazing Lands to Cultivated Forage Plants,"

published in 1913. Content of this Bulletin was based largely on his experiments in the Wallowa National Forest in the Blue Mountains. The Forest Service grazing studies in Oregon had been undertaken in 1907 as cooperative projects with the Bureau of Plant Industry.

The literature of early range research frequently repeats several questions: When is rangeland ready for grazing in the spring? How intensively should forage be grazed? When should grazing on mountain range stop in the fall? What species provide best nutrition for various classes of animals? How can we evaluate present condition of a range area? How can we tell whether a given area is improving or becoming further depleted? And many others. These questions were constantly in Sampson's mind and in the minds of his colleagues and successors.

Sampson's studies pointed the way toward answers to these questions, and his Bulletin on plant succession enunciated many useful principles. Forsling carried many of Sampson's inquiries further, but he inclined to test performance of individual species and different systems of grazing under actual field conditions rather than by the precise measurements that could be made in the laboratory, greenhouse, and nursery.

In 1938, Lincoln Ellison came to Intermountain Station and embarked on numerous and varied studies. The variety may be accounted for partly by the catholicity of his intellectual interests, partly by the fact that he regarded the range complex as an integrated whole.

Ellison was remarkably aware of the complexity of the range, of the problems incidental to its use, and of the numerous and contradictory opinions of persons who had studied them. One of his early publications at Intermountain Station (Ellison and Croft 1944) recognized existence of numerous contrary opinions about range and its use:

> *With the great divergences in opinion that exist at present, it is unlikely that the entire task of judging range condition and trend can be revolutionized overnight. Yet it is reasonable to believe that a careful appraisal of the elements making up mountain range, and an analysis of the significance of the indicators commonly used in judging range condition and trend, will provide a basis in fact which will be one step toward more uniform agreement among range managers.*

Ellison viewed range-watershed as a complex total comprised of biotic community, soil, climate, and topography — plus their interrelations; in short, he conceived the total as being something more than merely the sum of its parts, and an important constituent in this difference was what he called "balance," an element equated with the health of the range. He considered orderly successional change to be a normal condition of the range complex. This concept of balance of elements and health of range is implicit in the following statement of objective of range management (Ellison and Croft 1944, page 22):

> *The basic purpose in range management is to maintain the resource in such a condition that it will supply man with a maximum of the products and services he needs, or if the resource is already depleted, to restore it to that condition. The products for which satisfactory condition is to be attained are primarily water and forage, and in certain places there may be additional demands for timber or compliance with certain esthetic standards, depending on the use being made of the land. The purposes of range management, whatever they may be, require a combination of effective plant cover and stabilized, productive soil, and this combination must be sustained.*

Beyond this, he believed that the best condition attainable for mountain range was likely to be much different from the optimum condition of range in a valley or plains area. He accepted the general principle of plant succession set forth by Sampson, Clements, and others; namely, that soil and vegetation develop concurrently. He strongly believed that condition of the soil was the basic consideration for judging condition of a range rather than the state of the soil's vegetal cover. For him, the fundamental objective of range management was achieving a condition of balance between

the biota, soil, topography, and climate. Hence the best management for an area of steeply sloping range would be different from best management for gently sloping or flat land. For the steep slope, good management was "far less a question of whether the biotic community is climax or subclimax . . . than it is a question of maintaining a vegetal cover of some kind on the slopes which will keep the soil in place."

The fundamental objective of range management, he and Croft (1944) wrote, "is or should be *balance*, the standard of satisfactory condition *a balanced complex.*" Production of water, streamflow, and forage was a secondary objective. Having thus broadly stated fundamental objectives of range management, they described means by which the manager could determine the present condition of his range, by which he might determine whether it was better or worse than it had been, and by which from time to time he could tell whether its changing condition showed improvement or deterioration (Ellison and Croft 1944, page 26).

Ideally a manager should have available as basis for comparison some "natural" (i.e., ungrazed) area in pristine or near-pristine condition (Ellison 1949a). With this as a standard for comparison, he could determine how much vegetative cover (including species) and how much soil had been lost as a result of overstocking, overgrazing, trampling, and other types of abuse. In judging range condition, the manager should use this comparison as a *guide*, not as a *measure*, of an area's potentialities.

Ellison reiterated his earlier stand on the primary importance of soil: " . . . a basic criterion of range condition is degree of soil erosion, and a minimal requirement for satisfactory condition is normal soil stability." His second basis for judging range condition was the composition of the forage on that range, but he stated emphatically that soil stability was by far the more important. He exploded the myth that range condition could be attributed to weather. Climate was another matter — essentially, he said, "a constant"; hence its inclusion as one element of the range complex. Hence also his great interest in the climatic records begun at Utah Experiment Station some 30 years earlier and in the climatic studies that had been continuing since then.

In 1954, Ellison published a monograph in which he summarized the ecological information related to the subalpine zone of the Wasatch Plateau and reconstructed the character of the original vegetation there. He used data from some of the meter-square quadrats established by Sampson and charted at intervals since then; old photographs, range survey records, and data gleaned from many of his own studies provided additional useful information. To understand this vegetation it was necessary to work out salient characteristics of soil development and primary succession; consequently some of Ellison's conclusions conflict with those developed earlier by Sampson (1919b).

Ellison's major change in successional concepts was to identify the mixed upland herb association as the original vegetation on level areas and moderate slopes. Sampson had considered the "wheatgrass consociation" to be a seral herbaceous cover which was subclimax to the true spruce-fir climax. Ellison's mixed upland herb association is characterized by an abundance of tall perennial forbs such as tall bluebells *(Mertensia arizonica* var. *leonardi)*, sweetanise, and western valerian *(Valeriana occidentalis);* and various grasses such as slender wheatgrass and mountain brome. Because of the heavy and widespread overgrazing, Ellison found very little area covered by this original vegetation. However, he described in detail the various seral communities and their successional patterns.

A posthumous article by Ellison (1960) brought together all of the known information about the influence of grazing on plant succession on rangelands. It reviewed the effects of grazing and artificial clipping on plant vigor and survival; it also discussed the effects of herbage removal on microclimate, soil moisture, and incidence of fire. In conclusion he stated one of the great unsolved problems of range management:

> *The fact that, under the apparent handicap of millennia of grazing, most of the dominant species of the world's herblands are palatable plants, not only to buffalo and elk but to domestic livestock, is very impressive indeed. It suggests both that the adaptive process in evolution is ex-*

ceedingly complex and that perhaps we have been unable to discover a dependence of plants on grazing animals which is real and important. This is certainly to be reckoned one of the notable paradoxes of nature. Thus, in spite of all our study and thought, from the observations of herdsmen before Abraham's time to the results of scientifically designed experiments in the present day, we have very little real comprehension of what is perhaps one of nature's simpler mysteries.

Climatic Studies

Climatic studies were started early in the life of the Utah Experiment Station, and throughout the Station's history three major types of such studies have been continued. In his report of the Station's first year of work, Sampson wrote: "In order to propose experimental work intelligently one of the essential and initial steps is to study the conditions which control vegetation, stream flow and the like." As a preliminary to the studies of erosion on the Wasatch Plateau, measurements and records of the temperatures of air and soil and of precipitation and soil moisture were made at 10,000 feet. Thus began the years of recording of temperatures and precipitation on Watersheds A and B and later on other areas. Records of temperature and precipitation on Watersheds A and B constitute the first major studies of climate in this particular area; of course they had immediate direct bearing on the erosion studies; additionally, over the long term they provided important information used in the plant studies that were part of the revegetation phase of the grazing and range program.

The several plant communities have their individual requirements for moisture, sunlight, warmth, etc.; so a second set of studies was undertaken at the Station to (1) obtain a comparison of the climatic requirements of the main plant communities and (2) determine quantitatively the relation between local environmental factors and plant growth.

In 1913, Sampson set up meteorological stations at elevations of 7,100, 8,700, and 10,000 feet in the heart of the oakbrush, aspen-fir, and spruce-fir associations, respectively (Sampson 1918a). At these stations the major climatic factors (air temperature, precipitation, evaporation, barometric pressure, wind velocity, and sunshine) were recorded so that many environmental characteristics of each type-zone were well known. Study of the influence of weather on the development of plants began in 1915 and continued through 1916. The plants used for study at each weather station were a pedigreed strain of Canadian field pea, cultivated wheat, and native mountain brome. They were grown in potometers protected by screens. In the potometers two types of soil were used: infertile clay loam typical of areas where erosion and washing had diminished the humus and soluble salts, and fertile clay loam that had not been subject to erosion and washing.

This study produced voluminous and varied information about the three types of plants and about the climate of central Utah. Sampson's report also includes a wealth of information about techniques of the study and about capabilities and limitations of the equipment used in it. His correlations between environmental factors and plant growth and other physical activities were profitable reading for ecologists and botanists in his own time and are still informative a half-century later.

Sampson's study showed that growing seasons averaged 120 days in the oakbrush type, 105 in the aspen-fir, and only 70 days in the spruce-fir type. Average annual precipitation was greatest in the aspen-fir type but only slightly greater than in the spruce-fir association. Later studies by Lull and Ellison (1950), based on longer periods of time, indicated that precipitation increases with elevation; thus, the spruce-fir zone had the highest precipitation. Precipitation in the oakbrush type was barely half that in the higher elevation aspen-fir type (Sampson 1918a). Evaporation during the growing season was, as would be expected because of high temperatures and low humidity, greatest in the oakbrush type; but high wind velocity in the spruce-fir type (about 100 percent greater than in the types immediately below) resulted in evaporation comparable with that in the oakbrush. Both duration and

intensity of sunshine are practically the same at all elevations.

Costello and Price (1939) published results of much more elaborate studies that had extended over a longer time (1925-1934). The purpose of their Bulletin was to give detailed guidance in solving certain problems in range management — specifically to answer the persistent question: When is range ready for early season grazing? Costello and Price's study confirmed several of Sampson's main conclusions; namely, that:

1. Rate of maturity of plants decreases directly as heat units decrease at successively higher elevations.

2. Amount of water required to produce any unit of dry matter is greatest in the oakbrush zone, lowest in the aspen-fir zone, and intermediate in the spruce-fir zone; these relations coincide with the intensities of evaporation in the respective zones.

3. Total and average length of leaves and total dry weight produced are greatest in the aspen-fir zone and less in the other two zones.

4. Stem elongation is greatest in the oakbrush zone, intermediate in aspen-fir, and least in spruce-fir; this appears to be determined largely by temperature.

5. Production of dry matter appears to vary inversely with evaporation, but temperature also appears to be important.

One interesting and significant result of the Costello-Price study was discovery of the importance of the date of snowmelt in the spring. This date varies considerably from year to year, depending on depth of snow accumulation during the winter, temperatures during the melting period, and elevation. Progress of the entire growing season appears to be so closely related to this date that, given a 10-year average date for snow disappearance and the current year's deviation from that date, one can predict with surprising accuracy the dates when plant growth will start, when flower stalks will appear, when flowers will bloom, and when seeds will ripen. This is extremely useful, since the date when flower stalks appear indicates when a range area will be ready for grazing, and the "seed ripe" date is useful in determining when deferred grazing may begin. Seasons that begin early, late, or normal tend to remain so. Of course, during early growth a plant may be thrown off schedule by some extreme variation of weather from the normal.

Costello and Price's system for predicting dates of successive stages of plant growth was based on regression equations, which in turn were developed from data recorded for individual species at different elevations through a series of years. They checked reliability in 1935 by observation of development of individual plants at 50 staked locations over a large area at the head of Ephraim Canyon at elevations between 9,000 and 10,000 feet. They found that rate of plant development varied within and between classes of vegetation and that variation between stages of development of forbs and browse was much greater than for grasses. Costello and Price also confirmed the observations of Sampson and Malmsten that for each 1,000-foot increase in elevation the date of vegetational readiness is delayed about 18 days on south exposures and about 11 days on north exposures; at high elevations this variation is reduced.

Even though subject to considerable error, the methods for estimating range readiness for spring grazing devised by Sampson, Malmsten, Costello, and Price were a great improvement over rule-of-thumb estimates that had been used previously.

■ Plant Nutrition Studies

During part of the same time that Price, Evans, Costello, and others were studying the influences of climate on plant development, Price and Edward C. McCarty[9] were studying processes of growth and food storage for mountain brome, sticky geranium *(Geranium viscosissimum)*, coneflower *(Rudbeckia occiden-*

[9] *McCarty was head of the Botany Department of Riverside Junior College in Riverside, California. During summer months of 1932-1936, Intermountain Station employed him as Associate Forest Ecologist to carry out growth studies on several mountain range forage plants.*

talis), and slender wheatgrass. McCarty's studies of mountain brome demonstrated that its annual growth was in well marked cyclical stages. He also showed that growth rates vary at different times during a season and that a plant's supplies of nutrients decrease whenever the plant speeds up its growth (McCarty 1938).

McCarty pioneered physiological research concerning food storage and depletion related to phenology and clipping. His work has been widely quoted in range management literature and has inspired much similar work on other species.

The pattern of growth of mountain brome was characteristic in a general way for other forage plants found commonly on high-elevation range. The final report on these studies, a Bulletin published after McCarty's death (McCarty and Price 1942), carried specific recommendations for management of range on the Wasatch Plateau and similar areas. Grazing such areas, this report advised, "should be so coordinated with the critical growth and developmental stages of the principal perennial forage plants that the plants may assimilate and store sufficient foods to maintain growth and produce herbage for forage in subsequent years." Harvesting plants during their normal period for storing food prevents this storage; so grazing should be slackened then. Early grazing (plants 4 to 6 inches high) and grazing when herbage is dry or drying seemed to them to be well timed, but they cautioned against grazing so early that plants would be uprooted and trampled. They advised moderate grazing of mountain brome and slender wheatgrass (to a height of 3 or 4 inches at approximately monthly intervals) as "the key to practical and sound continued use of the annual forage crop produced on high western mountain ranges." Finally they restated one of Sampson's ideas and they urged rotation of grazing so that no given area would be grazed at the same time in successive years. "This provision," they wrote, "will allow for the production of seed and the reseeding of the range previously found to be necessary and may also obviate the necessity of slackened grazing during the critical periods of plant growth." This is one of the basic principles of the rest-rotation grazing systems now being widely applied.

■ Silvicultural Studies

Though Raphael Zon was one of the first men to approve establishment of the Station and some of the early studies suggested by Sampson, silvical research has never been a major activity at the Great Basin Station. As early as 1917, the Annual Report of the District Investigative Committee[10] for District Four stated: "It has been the feeling from the beginning that the Utah Station is not located advantageously for the prosecution of the greater part of our silvicultural investigations which are to a large extent local and not representative of those parts of the District in which silviculture is of primary importance. Our most important forest types are yellow pine, Douglas fir and lodgepole, and of these yellow pine is the most important." The committee concluded by recommending establishment of a silvicultural experiment station in central Idaho. This statement contrasts sharply with W. R. Chapline's comment in a letter to The Forester in 1922:

> *The [Great Basin] Station is fortunately situated, in that it is located where the northern and southern flora of the western United States meet, so that conditions that cover a wider area perhaps than any other single Station could cover are found here.*

However, the Utah Experiment Station was involved in one major silvicultural project that still has interest even though it was terminated many years ago. This was a study of the possibility of growing merchantable timber, specifically ponderosa pine, in the oak-brush zone.

[10] *Members were L. F. Kneipp, District Forester, Chairman; W. N. Sparhawk, Forest Examiner, Secretary; C. B. Morse, Forest Supervisor; Homer E. Fenn and C. G. Smith, Assistant District Foresters; and Arthur W. Sampson, Director of Utah Experiment Station.*

An ecological phenomenon that intrigued many early foresters was the so-called "pineless belt" between west central Montana and the Gulf of California. This area, several hundred miles wide in some places, is not devoid of pine but it naturally supports very little ponderosa *(Pinus ponderosa)* — or western yellow pine, as it was formerly known. It is a brushland belt running through the center of the usual habitat of ponderosa pine (Baker and Korstian 1931). The brushy vegetation is of several types found commonly throughout mountainous areas in northern and central Utah, southeastern Idaho, and western Wyoming that would normally be expected to support forests of ponderosa pine. The Utah Experiment Station was well within this belt, and the Transition zone in Ephraim Canyon supports abundant growth of oakbrush (fig. 13).

Figure 13. — The oakbrush zone in Ephraim Canyon where F. S. Baker and C. F. Korstian planted hundreds of seedlings of ponderosa pine and other conifers.

In this oakbrush zone, F. S. Baker and Clarence F. Korstian carefully studied climatic, soil, and other factors that might account for the absence of ponderosa. At the same time, they established another study area, some 25 miles distant on the east side of the Wasatch Plateau, where ponderosa grows in commercial stands. Baker's diary from February 7 to October 5, 1916, records planting of some 4,500 trees within a 2-month period. Of these, 2,000 were ponderosa pine; the rest were lodgepole *(P. contorta)* (400), Douglas-fir *(Pseudotsuga menziesii)* (1,000), Norway spruce *(Picea abies)* (700), and western larch *(Larix occidentalis)* (400). At the "oak-brush station" (apparently the area now labeled Plant Development Station 2) and in the adjacent area one can today see many trees from these early plantings. They vary from 30 to 50 feet in height, have diameters of 8 to 10 inches, and look reasonably thrifty. A few may be seen beside the Ephraim-Orangeville Highway (fig. 14), as many of them are not more than 100 yards from the road. Close in-

Figure 14. — Ponderosa pine trees planted by F. S. Baker about 1915 in the oakbrush zone, as seen from the Ephraim-Orangeville road in 1970.

spection of the plantings, though, reveals no regeneration.

Baker and Korstian reported that distribution of rainfall during the summer months in these brush areas in Utah "is notably different from that either to the north or south;" also that "deficiencies in July and August precipitation, combined with the fact that the rainfall usually culminated in August shortly before the early autumn frosts occur, make it impossible for the species to reproduce." They noted further that "the generally calcareous, heavy, fine-grained soils of the brush lands are prevailingly unsuited for western yellow pine." They were convinced that distribution of rainfall primarily determines the "pineless belt" and that details of its boundaries resulted chiefly from local differences in soils. The intense competition from the established brush cover was another factor limiting good growth of ponderosa pine.

F. S. Baker also did a great amount of work on aspen. Sampson (1919a) did some early work on aspen silviculture but it was mainly incidental to the study of the effect of grazing upon aspen reproduction. Baker's (1925a) major publication on the subject was the first to describe the phenology, growth, form, root systems, and the climatic, moisture, and soil requirements of aspen in detail. It was also the first comprehensive work on growth, yield, and management of aspen in the West. A major part of the publication was directed to the rate of growth and yield of aspen on different sites as a basis for management.

As part of his study, Baker established an elaborate set of permanent plots to determine if aspen timber production could be increased by thinning. In general, he found that thinning increased the production of wood in the form of sprouts and young trees but did not appreciably increase growth rates of larger trees. The detailed records on these permanent plots are invaluable historical base data on the ecology of aspen and are continuing to be used in current research. In 1970, Kimball Harper of the University of Utah and Robert Pfister of the Intermountain Station remeasured the trees on these plots to determine the rates of growth and the mortality of the aspen trees.

Baker and other early workers recognized that the aspen type is perpetuated by fire and, because of prevalent natural fires, aspen has occupied many sites for very long periods of time. In the absence of fire, aspen is succeeded by conifers. Baker discussed the relative values of aspen and conifer on the same site. Based on the economics of the time he concluded that income from aspen would be lower than from conifer and that "there can be no point, therefore, in trying to maintain an aspen management type." In recent years the validity of this conclusion has been questioned by many who feel that the multiple benefits of aspen, including grazing for livestock and game, habitat for many birds and small mammals, fire resistance, and esthetics, outweigh the value of conifers for timber production on many sites.

Korstian, like many other close observers of plant life in mountainous areas of the West, noted the striking zonation of vegetation in a regular series of altitudinal belts in Ephraim Canyon and elsewhere. This altitudinal zonation, he believed, is important to the silviculturist and to the range management specialist because many of the problems of the growth and regeneration of forests and the maintenance of range can be solved best through determination of the soil and climatic requirements of the different species in each zone, a point well demonstrated by the ponderosa pine study just described. In reforestation, Korstian (1924b) wrote that success depends on knowing the causes of successful growth and establishment of individual species and likewise knowing the causes of failure or partial failure of other species in the same environment. Since the problem appeared to be based on moisture requirements and availability, he launched a study of the density of cell sap in a variety of plants, including trees, found in several altitudinal zones from 4,500 feet to the summit of the Wasatch Mountains. This study, he believed, had implications for both silviculture and range management. However, despite the considerable detailed work, its results never were put to much practical application.

Rodent Studies

From time to time, reports of experiments refer to rodent damage — occasionally to "severe" rodent damage, sometimes to "significant" or even "excessive" damage — but they seldom particularize. One unidentified author noted that rodent damage in the oakbrush zone in 1932 seemed excessive, but he did not tell what kind of rodent was guilty. All sowings and plantations in the nursery that year were cut off by rodents, and this just before seed maturity, so that it was impossible to collect seed that season. In an aspen area, rodents cut about 90 percent of crested wheatgrass, and at Major's Flat they cut all grasses from 90 to 100 percent. Sometimes this author named pocket gophers; occasionally he specified mice or voles.

Gopher damage was of several sorts: some was consumption of roots, plants, or plant bases for food; some was the creation of mounds on the soil surface. Where workings were heaviest, there was usually a change in plant cover to a lower weed stage. Douglas knotweed *(Polygonum douglasii)* and groundsmoke *(Gayophytum ramosissimum)* seemed to become established early on disturbed earth. One may infer that Ellison's interest in damage by rodents stemmed from his conviction of the importance of soil condition as a fundamental part of the health of the range. He seems to have been the first to give serious thought to the questions of what kinds of damage rodents did to the range, and in what amounts.

When Ellison began serious study of gophers (chiefly *Thomomys talpoides moorei)* about 1940, he was aware of the divergent opinions about gophers' influence on the range (Ellison 1946). Some thought the gopher was a necessary part of Nature's economy: presumably, he deepened and fertilized mountain soils, and his winter casts might check erosion and overland flow of precipitation. But others contended that gopher diggings were a prime cause of accelerated erosion. As observers' opinions varied regarding the net effect of gopher diggings, so did their estimates of volume of earth these animals moved. Ellison's measurements in 1941 indicated annual soil displacement at 5 to 6½ tons (4.6 to 6.2 cubic yards) per acre. In 1942, serious study of gopher activity was begun by establishing a 4-acre, rodent-proof fenced plot on the summit of the Wasatch Plateau. This study was cooperative with the Fish and Wildlife Service and aimed to determine the effects of gophers on vegetation. Annual trapping periods in July and September, directed by C. M. Aldous, Biologist with the U. S. Fish and Wildlife Service, reduced populations from an average of about 24 per acre to from two to eight per acre (Ellison and Aldous 1952). Total effect of gophers on vegetation appeared to be slight at most. Common dandelion *(Taraxacum officinale)* decreased where they were present, but mountain dandelion *(Agoseris* spp.) did not. Grasses and sedges *(Carex* spp.) appeared to increase slightly. On areas subject to compaction under livestock grazing, gopher work seemed to help keep soil loosened.

Density of gopher population, like volume of their work, varied by location. Gophers were not active in timber or in brush; they worked most in the low herb type. Ellison's observations indicated that gopher tunnels seemed not to be a source of erosion from either snowmelt or torrential summer rains. On erosion pavement and other areas where topsoil and cover had been lost, their surface mounds seemed to provide a relatively favorable seedbed.

Ten years' observations and measurements provided a body of documented information about gopher influences on mountain rangeland, but the question whether the total effect of gopher presence was deleterious was still open for argument. C. M. Aldous, who participated in the experiments at Great Basin Station, wrote after 14 years: "It is an open question whether gophers are responsible for bringing about or creating poor range conditions, or whether ranges in poor condition tend to attract pocket gophers" (Aldous 1957).

COOPERATIVE PROJECTS

Research organizations frequently require help from similar units and reciprocate by giving special help of their own. Cooperative projects with the Utah Division of Wildlife Resources, the Bureau of Sport Fisheries and Wildlife, and the Agricultural Research Service have been mentioned previously. Many other types of cooperative projects have also taken place at the Great Basin Station.

From time to time, Station personnel have responded to requests from schools and service clubs to discuss Forest Service research generally or Great Basin projects specifically. For several summers following World War II, the Station was locale for a 2- or 3-day outing for 4-H clubs in Sanpete County. Station facilities have been used for numerous training sessions for Forest and Region personnel. A 2-week Range Research Seminar (July 10-22, 1939) was attended by nearly 60 range management research specialists and administrators from all western regions and from Washington, D. C.[11] Over the years it has participated in occasional research projects of the Agricultural Experiment Station of Utah State University. The Station's long continuous record of climatic data for Ephraim Canyon and the Wasatch Plateau frequently has proved invaluable.

Since 1966, Intermountain Station has participated in a cooperative project in teacher training sponsored by the Utah State Department of Public Instruction. The Intermountain Region of the Forest Service also has participated actively in this development of instructional programs and in directing field trips and related activities. The project essentially is 5-day workshops designed to prepare teachers in elementary and secondary schools to teach fundamental concepts of conservation and of improvement in quality of the environment. The 5-day sessions are planned for groups of about 40 teacher-students, and the number of sessions per summer has varied from one to four.

Instruction includes demonstration of the function of vegetal cover in reducing overland flow and stabilizing soil, identification of useful plant species, identification of numerous birds and mammals found in Utah wildlands, and demonstration of effective techniques for teaching fundamental conservation concepts to young people in the elementary and secondary schools.

Response by the Department of Public Instruction and by the teachers has been enthusiastic. An interesting and unexpected byproduct of this project has been the changing of many teachers' image of the Forest Service. Until their direct contact with it at the Great Basin Station, many of them had presumed the Forest Service was largely if not solely a law enforcement or fire protection agency. They have been literally amazed to learn about the Forest Service activity in research and management relating to recreation, wildlife habitat, watershed protection, livestock forage, timber production, and other uses and values of wildlands.

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[11] *See Proceedings of Range Research Seminar. Forest Service, U. S. Department of Agriculture. 414 p. (n.d.) This volume contains 35 professional papers and discussion of them.*

APPLICATIONS

The "proof of the pudding" principle applies with full validity to research; but here the "proof" is in the use or application. Results of much of the research at Great Basin are now in use or have been used for many years; but it is virtually impossible to document details or specific instances of adoption of individual results. It is certain that research pioneered and carried out on, or headquartered at, the Great Basin Station has touched every aspect of range management. Early work proved conclusively the relationship between overgrazing and depletion of the vegetal cover and destructive flooding. McCarty's work on food storage cycles of plants was the first research to provide a scientific basis for management and utilization of forage plants. Ellison's work on condition and trend criteria was quickly incorporated into National Forest Administration range allotment analysis procedures and is the basis for many criteria in use today by many land management agencies. Seeding work done by Plummer, both on high mountain areas and in lower oakbrush and pinyon-juniper areas, has provided information on adapted species that has been widely used by all land management agencies in their revegetation work.

The principle of deferred-and-rotational grazing, developed and advocated by Sampson, Forsling, and numerous successors has been a subject for continuing study and refinement. Many recent studies of deferred and rotation grazing have been made at Forest and Range Experiment Stations throughout the West. These practices have proved useful, and numerous variations have been made to the original systems; but there is no way of knowing how many range managers use them in any form, much less how they learned about them. Rest-rotation grazing (Hormay and Talbot 1961), modifications of which are so widely being put into practice now on public and private ranges, is but a variation of the deferred- and rotation-grazing schemes developed by Sampson.

The ideas of the possibility of and necessity for management of rangeland were spreading about the time the Utah Experiment Station was established. Land-grant colleges began by giving single courses in the subject; as more needs became evident and more information was developed, the number of courses increased, and what had been one man's specialty became a department; of course the ultimate development has been that both bachelor and graduate degrees have evolved, with range management as a major program. Utah Agricultural College (now Utah State University) offered its first course in range management in 1914 and established a curriculum in it in 1928. Montana State University offered its first course in range management in 1915, and Colorado Agricultural and Mechanical College followed in 1916. Courses in range at the University of Idaho and the Oregon State Agricultural College were taught first in 1917. Washington State College followed in 1919; University of California offered its first course in range in 1920 but did not establish a curriculum in it until 1953. The succession of years when courses were first offered reveals clearly that the idea of training young men in this subject had caught on.

Sampson's prolific writing about range management and related subjects continued after he left the Great Basin Station to teach at the University of California. Within a few years he published three books that received wide acceptance as textbooks and reference works (Sampson 1923b, 1924, and 1928). These books were based largely on research at the Great Basin Station and they became the

"bible" for range managers at that time because no other texts were available. Of course, with the passage of time and the proliferation of college courses in range management, the number of books on the subject also increased.

The early plant studies, begun as part of the projects in natural and artificial reseeding, developed into rather elaborate studies of fundamental plant behavior that extended the bounds of early ecological knowledge. These have been discussed already in the section "Ecological Endeavors."

To a degree, what happened in the development of range management was paralleled by the development of studies of watersheds, their management and maintenance. Treatments and studies of Watersheds A and B and of the nearby Carrying Capacity Pasture established beyond question the necessity for having certain minimal vegetal cover on high-elevation rangeland to prevent overland flow, flooding, and erosion following typical high-intensity summer storms. Principles discovered by study on the Wasatch Plateau were demonstrated effectively by Reed W. Bailey and others in treatment of the Davis County watersheds after disastrous mud-rock floods in the decade of the 1930's. The work at Farmington, like that at Ephraim, has generated considerable publication, and the Davis County Experimental Watershed has been visited by hundreds of scientists from the United States and numerous other countries who needed to learn fundamentals of flood prevention. We cannot say certainly whether development of the science of watershed management preceded the development of range management, but we may observe a certain paralleling. In central Utah, realization of the problem of watershed management appears to have preceded realization that range management was the key to its solution.

The management of mountain rangeland for the benefit of wildlife or for use by both wildlife and stock might appear to be a project of more recent origin. However, it was in the thinking of range management people by the decade of the 1940's. In his presidential address at the second annual meeting of the American Society of Range Management, Joseph F. Pechanec said, "One of the greatest challenges we have is to determine how by research, and to prove by practice that grazing livestock and big game in our forests and on our grasslands need not necessarily be damaging to the land, ruinous to the watersheds, and destructive of civilizations." Wildlife management, like range management and animal husbandry, has found its way into college curricula. As hunting pressures and interest in all forms of wildlife have increased, so has the need for improvement of wildlife habitat; hence the economic and political pressure for maintenance and improvement in game range. Study of game range and devising means for its improvement have been pioneered at the Great Basin Station, and application of the results of these studies has been rapid and successful, as has been mentioned above.

Continuing ecological studies at the Great Basin Station understandably have had important use in National Forest administration. What has been learned about total range, about condition and trend criteria, and about characteristics of numerous range plants has influenced policy in range administration. It has made the determination of the grazing capacity of allotments a matter of informed judgment and skill rather than a haphazard rule-of-thumb procedure. These studies have enabled Forest Service personnel and others to judge with some accuracy when grazing may safely begin in spring and when, in summer or fall, grazing should be stopped. Results of these studies have been used in training young foresters, and publication of these results by the Forest Service and in professional and trade journals has disseminated this information far beyond the borders of the United States.

Although much research at the Great Basin Station could be classified as "basic" or "fundamental," the studies have all been oriented to practical use. The information developed at the Great Basin Station has been applied in conservation of a great natural renewable resource, in determination of Forest Service policy for the administration of range areas and watersheds, and in training young foresters in certain fundamentals of their job. Research at the Great Basin Station has been anything but a narrow, restricted, "ivory tower" affair; rather it has been as wide open as the sunny hillsides and plateaus on which it has been done.

FUTURE PLANS

The Order Establishing the Great Basin Experimental Range assumes continued research that will have application in land management for many years ahead. The list of projects proposed for future study there includes:

1. Ecology and management of pinyon-juniper, spruce-fir, mountain herb, oakbrush, aspen, and associated plant communities and their relation to various environmental factors, particularly soils and weather.
2. Improvement and management of big game habitat.
3. Selection and breeding of improved shrubs, evaluation of promising selections, development of efficient seed-production technology, and development of effective procedures for shrub establishment in forest and range environments.
4. Wildlife-livestock relations in multiple use management.
5. Range-watershed rehabilitation.
6. Water-yield improvement through vegetative manipulation and structural measures.
7. Silviculture and management of aspen and associated conifers in relation to forage, water, and other multiple use values.
8. Forest recreation planning and management.

Other plans not mentioned in the Establishment Order include interdisciplinary studies in the functioning of the aspen ecosystem. Aspen is an important type in the mountains of Utah and surrounding States and furnishes valuable cover and forage for game and livestock, important watershed protection, some timber, and is an important part of the mountain scenery. Because of fire protection many aspen sites are now being invaded by conifers. The dynamics and economics of this change need to be determined so the land manager can intelligently either permit or prevent the replacement of aspen by conifer. The Great Basin Experimental Range will be an ideal place to conduct aspen ecosystem studies because of the abundance of aspen and because of the long history of vegetation and climatic records in the aspen as well as in other vegetation types.

Nearly a hundred meter-square quadrats are on or in the vicinity of the Great Basin Experimental Range; many of them were established by Sampson in 1913 or 1914 and have been sampled at irregular intervals since then. These records of vegetation change, along with corresponding climatic records, form a pool of data that will be invaluable for further study of the ecology of these plant communities and their response to changes in the environment.

The Intermountain Forest and Range Experiment Station is seriously considering possibilities for developing a visiting-scientist program that would attract outstanding university scientists to the Intermountain area for the summer months. The Great Basin Experimental Range has excellent possibilities for this purpose; it is easily accessible; it has a pleasant summer climate; living quarters are comfortable and attractive; and limited facilities for some kinds of laboratory work are immediately available.

RESEARCH PUBLICATIONS

The Forest Service has long maintained that no research project is completed until its results have been formally published or otherwise made available to workers. Over the 60 years since establishment of the Utah Experiment Station the volume of publication based on results of studies on the Wasatch Plateau and in Ephraim Canyon has been substantial. The bibliography that follows is a selective list of publications known to be based in whole or in part on research done there.

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BARK BEETLE RISK IN MATURE PONDEROSA PINE FORESTS IN WESTERN MONTANA

Philip C. Johnson

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COVER

Photograph taken on a study plot in the Piquett Creek Experimental Area, Bitterroot National Forest, Montana, shows a mature ponderosa pine forest; in the background is Boulder Peak, elevation 9,650 feet.

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ABSTRACT

The Ponderosa Pine Risk Rating System developed in California was studied in western Montana to determine whether it could effectively identify individual mature trees most frequently killed by the western pine beetle, Dendroctonus brevicomis LeConte, or the mountain pine beetle, D. ponderosae Hopkins (Coleoptera: Scolytidae).

Risk 3 and Risk 4 trees--the high risk trees of the four-rating system--comprised 20 percent of the board-foot volume of 12,000 merchantable, risk rated ponderosa pine trees at 35 localities. On study plots in 22 of these localities, ponderosa pine stands that remained undisturbed throughout the study initially contained 17 percent of their total pine volume in Risk 3 and Risk 4 trees. Risk 3 and Risk 4 trees, however, made up 76 percent of the volume of all ponderosa pine trees killed by populations of the two pine beetles on these plots during the study.

Ponderosa pine mortality from the two pine beetle species was consistently low during the study, amounting to a mean of only 15.5 board feet per acre per year on the 22 undisturbed study plots--an amount considerably less than the estimated gross ponderosa pine increment on the same plots.

Subsidiary information obtained from the study indicated that (1) external crown characteristics used by the risk rating system in California to delineate the risk of mature ponderosa pine trees to attack by the western pine beetle were equally effective for this purpose in western Montana; (2) Risk 3 and Risk 4 ponderosa pine trees, together, grew an average of 0.18 inch radially during one 10-year period of the study, and Risk 1 and Risk 2 pine trees grew an average of 0.43 and 0.31 inch, respectively; (3) in 15 mature ponderosa pine stands where soil characteristics were measured, Risk 3 and Risk 4 trees were progressively more abundant as the fertility, productivity, and water-holding capacity of the soils declined; and (4) the mountain pine beetle was not an important primary killer of mature ponderosa pine trees during the study, and it exerted little influence in predisposing low risk trees to attack by the western pine beetle.

It was concluded from the study that managers of mature ponderosa pine forests in western Montana can use the risk rating system to assess the susceptibility of these forests, or of individual ponderosa pine trees in them, to lethal attacks of the western pine beetle for 10 years or more during periods of endemic beetle populations.

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Old-growth stand of ponderosa pine on the McCrea Park risk rating plot near Alberton, Montana. The crowns of the overmature trees in this relatively dense stand exhibit varying decline in vigor symptomatic of increasing susceptibility of some trees to lethal attacks of the western pine beetle.

INTRODUCTION

During the 1940's, managers of ponderosa pine forest properties in the northern Rocky Mountain States displayed increasing interest in the possibility of using sanitation-salvage cuttings to prevent destructive outbreaks of the western pine beetle, *Dendroctonus brevicomis* LeConte (Coleoptera: Scolytidae). Their interest possibly stemmed from reports of tests and several operational applications of such cuttings made during the late 1930's in ponderosa pine forests in northeastern California and eastern Oregon wherein the cuttings were credited with reducing intolerable tree mortality from the pine beetle. During the mid-1930's, in this northwest fringe of the North American Great Basin, the concept of preventive control of the western pine beetle had become a reality as a result of the development of the sanitation-salvage cutting method (Bongberg;[1] Johnson;[2] Keen and Salman 1942; Orr 1942; Salman and Bongberg 1942).

Forest entomologists coined the term "sanitation-salvage cutting" to refer to a light silvicultural selection cutting designed to remove from overstory stands for utilization certain merchantable ponderosa pine trees judged to be potential breeding habitats for the western pine beetle. These trees are ordinarily of low vigor and readily identified as the Risk 3 or Risk 4 trees of the four-rating Ponderosa Pine Risk Rating System (see fig. 1) evolved by Salman and Bongberg (1942). Under this rating

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[1]J. W. Bongberg. Effectiveness of sanitation-salvage logging in reducing insect-caused loss, Blacks Mountain Experimental Forest, season of 1940. USDA Bur. Entomol. and Plant Quar., Forest Insect Lab., Berkeley, Calif. Unpub. Rep. May 12, 1941.

[2]Philip C. Johnson. Effect of sanitation-salvage cutting upon subsequent insect-caused pine mortality, Blacks Mountain Experimental Forest, progress report, 1937-1943. USDA Bur. Entomol. and Plant Quar., Forest Insect Lab., Berkeley, Calif. Unpub. Rep. May 31, 1946.

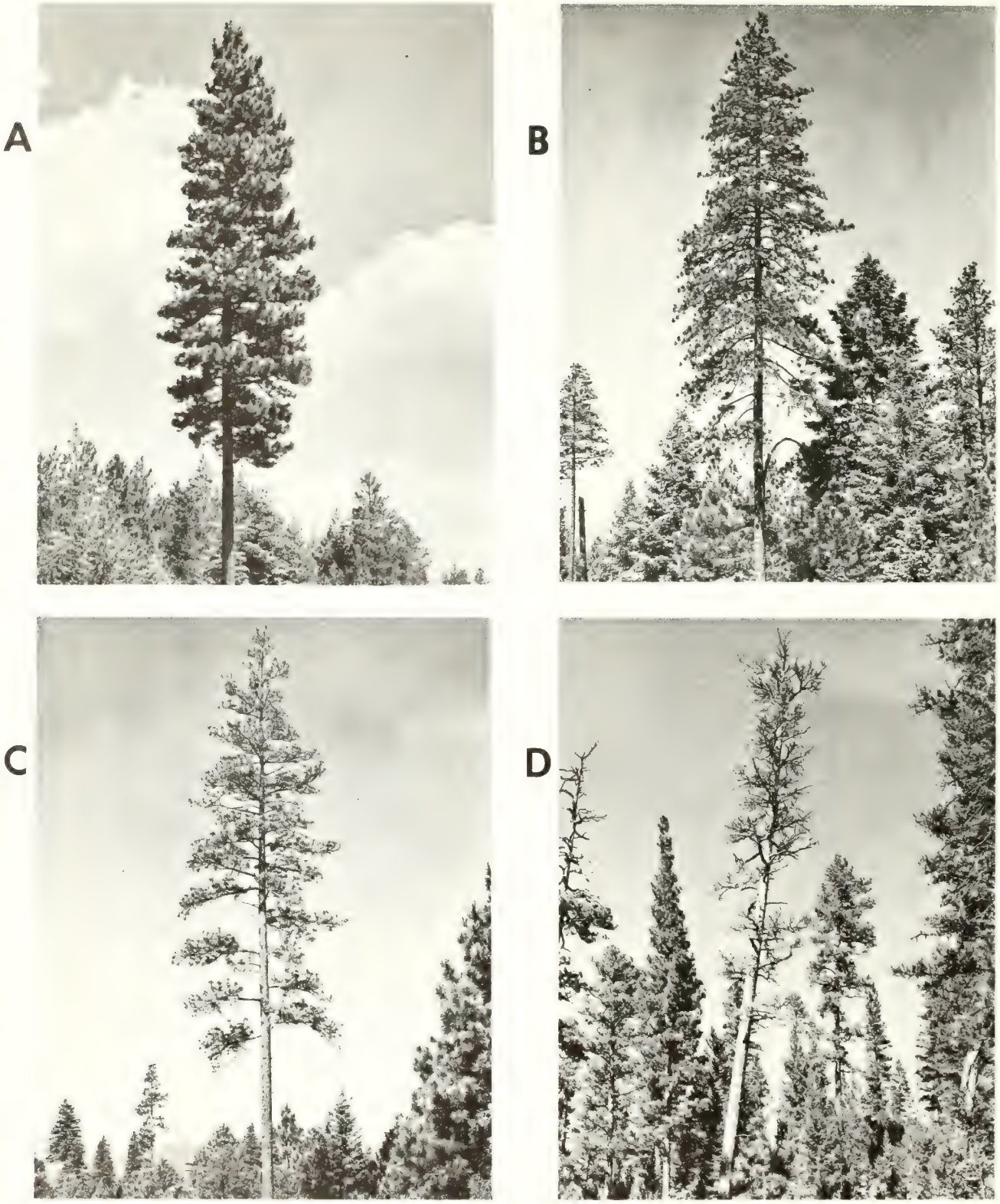

Figure 1.--Crown characteristics of ponderosa pine trees symbolizing each of the four ratings of the Ponderosa Pine Risk Rating System and the relative risk, or susceptibility, of trees in each rating to attacks by the western pine beetle: A, Risk 1 (low risk); B, Risk 2 (moderate risk); C, Risk 3 (high risk); and D, Risk 4 (very high risk).

system, such trees in northeastern California and eastern Oregon are rated as being either highly or very highly susceptible to lethal infestation by the pine beetle. Extensive tests made as late as 1959 have confirmed the capability of sanitation-salvage cuttings to minimize such destructive depletion of the ponderosa pine resource as occurred during the period from 1940 to 1959 in northeastern California and eastern Oregon (Keen and Miller 1960; Wickman and Eaton 1962).

Despite the apparent success of sanitation-salvage cuttings to control the pine beetle in the Pacific Coast States, several inherent differences in the ecology of ponderosa pine forests and the western pine beetle in the northern Rockies raised questions about use of such cuttings to achieve similar insect control benefits in this mountain region. Furthermore, ponderosa pine stands in the northern Rocky Mountains during the 1940's were experiencing environments favoring good tree vigor and growth. Almost nothing was known of the possible response of consequent endemic pine beetle populations to sanitation-salvage cuttings that might be applied as a control measure under these conditions.

However, this concern about the effectiveness of the cuttings was largely academic because information was not available on the adaptability in the northern Rockies of the Ponderosa Pine Risk Rating System upon which the cuttings relied. The rating system's effectiveness in identifying beetle susceptible trees to be removed from pine stands by the cuttings had to be determined before any tests of the cuttings as a beetle control measure could be undertaken in this region. To obtain this information, a study of the effectiveness of the risk rating system was undertaken in western Montana in 1948 by the Coeur d' Alene (Idaho) Forest Insect Laboratory of the former Bureau of Entomology and Plant Quarantine. The study was continued by the Intermountain Station until 1969.

In the study, we sought to determine (1) whether the western pine beetle has an affinity for attacking ponderosa pine trees classified as high risk, or beetle susceptible, using this rating system, (2) whether such attacks might be diverted by attractions created in low risk trees as a result of prior infestations in these trees by the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, or the pine engraver, *Ips pini* Say (Coleoptera: Scolytidae), or (3) whether the western pine beetle constituted a serious threat to mature ponderosa pine stands in the northern Rockies.

Endemic populations of the western pine beetle killed only minimal amounts of ponderosa pine timber during the 20-year span of the study. This and nearby harvest cuttings that made ecological islands of some of the study plots argued against further extensions of the study. Consequently, the study was terminated upon completion of tree mortality measurements of the 1968 beetle population.

EXPERIMENTAL PROCEDURE

Objectives of the study were to be achieved by annually measuring the mortality of ponderosa pine trees caused by the pine beetle over a 10-year period following the single initial risk rating of the trees. For this purpose, 35 plots having a combined net timbered area of 553 acres were established between 1948 and 1958 in widely scattered stands of virgin mature ponderosa pine in Montana west of the Continental Divide.

Financial limitations prevented the sampling of the heterogeneous pine stands in a manner that might statistically test the significance of possible differences in tree mortality rates in each of the several pine forest cover types of the Society of American Foresters (1954) or of the pine-dominating vegetation habitat types of Daubenmire and Daubenmire (1968) that might be represented in this region. Neither was it possible to make a sampling to determine possible differences in rates of beetle-caused tree mortality in relation to such stand factors as composition, density, or site indexes. These factors by themselves probably could not be used with sufficient accuracy to predict the amount of tree killing by the pine beetle in specific ponderosa pine stands as reported by Salman and Johnson.[3]

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[3]K. A. Salman and Philip C. Johnson. The forest insect hazard inventory of eastside forest areas, preliminary report on methods and their application. USDA Bur. Entomol. and Plant Quar., Forest Insect Lab., Berkeley, Calif. Unpub. Rep. Sept. 21, 1937.

Because of our concern with mature trees, the study plot stands were selected primarily on the basis of the descriptive qualities of their overstories. Reasonable homogeneity among plot stands was achieved by adopting minimal criteria for selecting them. They contained at least 10,000 gross board feet of ponderosa pine per acre in trees 11.1 inches in diameter breast height (d.b.h.) or larger. At least 50 percent of these trees were in the mature or overmature age classes of the Ponderosa Pine Tree Classification (Keen 1943). In effect, these were virgin, commercially operable pine stands.

All trees on the plots over 11.1 inches d.b.h. were measured and their gross board-foot volumes (Scribner scale) were later computed. Ponderosa pine trees on the plots were serially numbered, tagged for identification, risk rated, and classified by age and long-term vigor using the Ponderosa Pine Tree Classification. This provided a basis for the study of nearly 12,000 sawlog-size ponderosa pine trees containing a total gross volume of 9.3 million board feet. For phases of the study concerned only with the accumulated mortality of risk rated trees, this basis was reduced to 6,800 pine trees having a total volume of 4.8 million board feet on 270 acres because of experimental sanitation-salvage or random selection cuttings made on 12 of the plots during 1957 and 1958.

Stands on the plots were examined annually to locate and record the deaths of ponderosa pine trees caused by the western pine beetle or the mountain pine beetle during the previous year. To isolate and identify this source of tree killing, we recorded the deaths of trees caused by quick-acting lethal agents--windstorms, lightning, fire--or from other cambium-feeding insects[4] (Johnson 1966).

No fire-killed pine trees were reported during the study. Pine trees obviously killed by lightning or uprooted or lethally damaged by windstorms were recorded by their serial numbers and previously obtained dimensions and descriptions. Pine trees apparently killed from other causes were felled and their boles were systematically examined to detect and record the presence and distribution of attacks, if any, of the two pine beetles or of other tree-killing, cambium-feeding insects (Johnson 1967). Knowledge of the biology and phenology of the various insects involved was a requisite of the bole examinations. It was possible to identify the insect or insects that were infesting each tree bole and to determine which of them was probably responsible for the immediate death of the tree from (1) the observed progress of the construction of parent beetle egg galleries and larval mines, and (2) the metamorphic stages of the insects present.

The risk rating's concern with tree vigor suggested an investigation of soils on the study plots to determine whether a relationship existed between the presence of certain soil characteristics and the abundance of high risk trees in the plot stands. At the request of the Intermountain Station, soils on 15 of the risk rating plots were classified by the Soils Management Branch, Division of Soils and Watershed Management Branch, Northern Region, USDA Forest Service. A brief description of the methods used is quoted here from the report[5] of the completed classification:

> The soils on 15 research plots in western Montana were examined in the field. Preliminary identification of the soils was made. The relative depth and texture of the soils were particularly noted because they are

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[4]Notably, the pine engraver, *Ips pini* Say, or the California flatheaded borer, *Melanophila californica* Van Dyke (Coleoptera: Buprestidae).

[5]R. C. McConnell. Correlation between soils and bark beetle susceptibility classes for ponderosa pine stands, western Montana research plots. Unpub. Rep., USDA Forest Serv., Northern Region, Missoula, Montana. 6 p. 1966.

associated and express the potential storage of moisture. Higher storage of moisture should be associated with higher tree vigor and lower beetle risk susceptibility class. Indicators of soil depth and texture can be secured by observing land forms, kinds of materials underlying the soil, observations of deep road cuts, uprooted trees, mapping experience in the general area, and published soil survey reports. Important preliminary qualitative data on soils was quickly collected and first stratification of data was made. For qualitative determination of soil moisture it is expected that pits would eventually be dug in the plots, the soil profile described in detail, and samples taken for laboratory determination of moisture points, and fertility factors. At that time, detailed mapping of soil in the plots would be made in order to check soil uniformity and variation.

Another facet of the study sought information on the radial growth rates of mature ponderosa pine trees representing different risk ratings. This was done cooperatively with the School of Forestry of the University of Montana. Increment cores were extracted from 383 risk rated ponderosa pine trees at breast height on four plots. Mean tree ring widths for the last 10 years (1944-1953) were calculated for cores representing each risk rating group and comparisons were made of these means.

By 1958 it was apparent that objectives of the study could not be attained within 10 years because of continuing low levels of pine tree mortality that resulted from the endemic populations of the western pine beetle and the mountain pine beetle that persisted during the period. By agreement with cooperators, the study was continued for a second 10-year period. Hopefully, tree mortality from the two pine beetles would be sufficient at the end of this extended period to realize objectives of the study.

Extending the study posed a new question. Would the initial risk ratings continue to be valid during the second 10 years of the study? Changes in the initial risk ratings of some pine trees had been noted by research personnel throughout the first 10 years of the study. To ensure valid ratings during the second 10 years, the pine trees on 17 plots established before 1952 were re-rated in 1964 and 1965. This was done by trained forestry research technicians under the close supervision of the research entomologist in charge of the study. This procedure hopefully afforded continuity as well as a minimum of personal bias in the ratings.

DESCRIPTIONS OF THE PLOT OVERSTORY STANDS

Measurements revealed that the structural and ecological values of the predominantly ponderosa pine overstory stands varied among the plots and, to a lesser degree, within the plots. These values substantiated the long-observed variability of mature ponderosa pine stands in mountainous western Montana. Here, rapidly changing topography is responsible for complex mosaics of plant habitats that not only produce innumerable combinations of vegetation habitat types within relatively small areas but also variations in the productive capabilities of plants within these types (fig. 2). The differing combinations of descriptive values represented by the plot stands undoubtedly are repeated many times in stands of mature ponderosa pine throughout western Montana. It is almost certain, too, that many pine stands in this geographic area possess combinations of values not represented by the plot stands.

Forest Cover and Vegetation Habitat Types

Of the 35 plots used to sample ponderosa pine stand conditions, only six contained stands that represented the Society of American Foresters' interior ponderosa pine forest cover type (S.A.F. Type 237) in which ponderosa pine is strongly climax. This may indicate the relative sparseness of this type of pine stand in western Montana.[6] Most of the remaining plot stands represented the Society's ponderosa pine--larch--Douglas-fir forest cover type (S.A.F. Type 214) wherein ponderosa pine is strongly seral.

The plot stands represented several of the Daubenmires' vegetation habitat types. Although these types were developed from vegetation mosaics in eastern Washington and northern Idaho, current ecological studies indicate that some of them containing significant amounts of ponderosa pine are to be found in limited amounts in western Montana.[6] Among them are the *Pinus ponderosa/Festuca iddhoensis* (ponderosa pine/Idaho fescue), *Pinus ponderosa/Agropyron spicatum* (ponderosa pine/bluebunch wheatgrass), *Pinus ponderosa/Purshia tridentata* (ponderosa pine/bitterbrush), and the *Pinus ponderosa/Symphoricarpos albus* (ponderosa pine/snowberry) types in which ponderosa pine is climax.

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[6]Robert D. Pfister, Research Forest Ecologist, and Peter F. Stickney, Research Range Ecologist, Forestry Sciences Laboratory, Missoula, Montana. Personal communication.

Figure 2.--The heterogeneity of old-growth ponderosa pine stands in western Montana is illustrated here. Abrupt topography and occasional catastrophic fires, insect outbreaks, or windstorms are responsible for frequent changes in site conditions over relatively small areas and a resultant lack of continuity in the forest vegetation.

They also include the *Pseudotsuga menziesii/Calamagrostis rubescens* (Douglas-fir/pinegrass), *Pseudotsuga menziesii/Physocarpus malvaceus* (Douglas-fir/ninebark), and the *Pseudotsuga menziesii/Symphoricarpos albus* (Douglas-fir/snowberry) types in which ponderosa pine is seral. Roe[7] is of the opinion that some of the most productive stands of ponderosa pine in western Montana are to be found in some of these Douglas-fir habitat types.

Composition and Density

Overstory trees on 12 plots were exclusively ponderosa pine; however, the species probably was climax on no more than half of these plots. In contrast, 27 percent of all overstory trees and 11 percent of their gross board-foot volume on the remaining 23 plots were species other than ponderosa pine.

The most prevalent of these nonpine tree species was Rocky Mountain Douglas-fir, *Pseudotsuga menziesii* var. *glauca* (Beissner) Franco. This was followed by lodgepole pine (*Pinus contorta* Douglas) and western larch, (*Larix occidentalis* Nuttall), which occurred only sparsely on some plots.

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[7]Arthur L. Roe. Formerly, Research Silviculturist, Intermountain Station, Ogden, Utah. Personal communication.

Figure 3.--Dense stand of advanced reproduction of Rocky Mountain Douglas-fir under a well-stocked overstory of mature ponderosa pine on a risk rating plot in the Piquett Creek Experimental Area, Bitterroot National Forest, Montana.

The seral nature of ponderosa pine in most of the plot stands is only partially indicated by these nonpine tree species in the overstory. More conclusive evidence of ponderosa pine's serality in the plot stands is the intrusion in recent years of increasing amounts of nonpine reproduction in the understory stands of the plots. Dense stands of Rocky Mountain Douglas-fir, in particular, now occupy the ground under the pine canopy on parts of some plots (fig. 3). Stimulated by effective control of wildfires and by growing conditions that have favored nonpine species during the past three decades, resultant nonpine reproduction is preventing or crowding that of ponderosa pine in many of the plot stands.

Observations disclosed that the pine understory on most of the plots was so sparse that its maturation will produce timber yields far short of those expected from ponderosa pine site indexes 70, 80, or 90 that the plots represent (Meyer 1938).

The mean stocking density for all species ranged for each plot stand from 14.7 to 44.9 trees per acre (12,920 to 25,730 gross board feet per acre). The mean stocking density for ponderosa pine alone ranged for each plot stand from 14.7 to 37.3 trees per acre (9,990 to 25,200 gross board feet per acre) (fig. 4). The stocking densities for pine and nonpine species are shown for each of the 35 plots in tables 1 and 2.

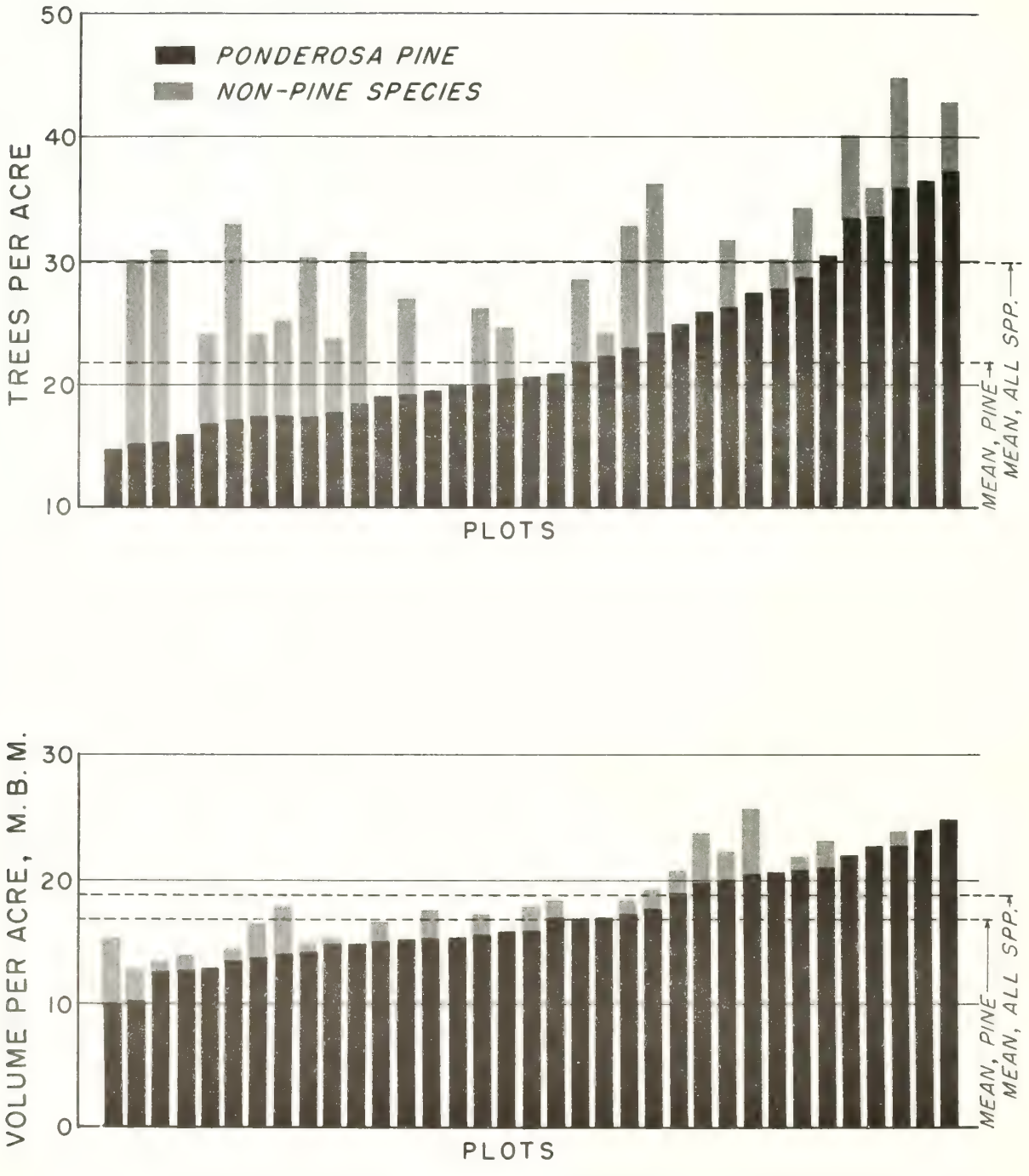

Figure 4.--Variation in the mean number and gross board-foot volume of overstory sawlog-size ponderosa pine trees per acre on 35 plots in western Montana. The horizontal position of the plots is not necessarily the same in the upper and lower histograms.

Table 1. [illegible]

Owner	Plot	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Anaconda Forest Products						
[illegible]			17.4	-	-	-
Fish Creek Forks		10.0	[illegible]	[illegible]	0.9	[illegible]
[illegible]		[illegible]	17.1	[illegible]	5.1	21.1
Longpre Cabins		8.9	[illegible]	4.8	.7	12.8
Fishtrap Creek		10.0	[illegible]	[illegible]	[illegible]	[illegible].1
Little Thompson River		10.0	[illegible]	5.2	.1	[illegible].0
North Fork Little Thompson River		10.0	[illegible]	3.7	1.2	1.6	40.1
Pleasant Valley		10.0	[illegible]	[illegible]	[illegible]	[illegible]	36.
Jake Little Ranch		10.0	27.9	[illegible]	[illegible]	[illegible]	[illegible]
Lost Prairie		10.0	30.7	[illegible]	[illegible]	[illegible]	30.
Lake McGregor		8.5	[illegible]	[illegible]	4.1	[illegible]	44.6
Glacier Park Company							
Little Bitterroot River		10.0	28.9	-	[illegible]	[illegible]	34.4
St. Regis Paper Co.							
Loon Lake		5.4	27.7	-	-	-	27.7
Bitterroot National Forest							
Bear Creek Saddle		8.4	20.6	-	4.1	[illegible]	24.7
Overwhich Creek		10.0	25.1	[illegible]	[illegible]	[illegible]	25.6
Piquett Creek	B[2]	22.0	19.7	-	[illegible].1	[illegible]	29.8
	[illegible]	22.0	16.2	-	10.1	-	26.3
	[illegible]	22.6	20.8	--	10.1	-	30.9
	[illegible]	22.6	26.1	-	10.1	-	36.2
	[illegible]	15.8	14.7	-	10.1	-	24.8
	[illegible]	22.5	21.1	-	10.1	-	31.2
	[illegible]	22.7	17.5	-	9.4	-	26.9
	[illegible]	24.0	20.2	-	6.0	-	26.2
	[illegible]	[illegible]	[illegible]	--	4.4	-	22.4
	K	22.5	24.2	--	4.6	-	28.8
	L	21.3	18.5	-	12.7	-	31.2
	P[3]	22.5	[illegible]	-	10.1	-	25.1
	[illegible]	22.4	15.2	-	14.9	-	30.1
	[illegible]	[illegible]	23.4	-	10.0	-	33.4
	[illegible]	21.9	[illegible]	--	7.7	-	27.1
	[illegible]	23.7	21.9	--	7.0	--	28.9
	[illegible]	22.5	[illegible]	--	6.9	--	24.5
	R	22.5	[illegible]	--	5.9	-	21.4
Helena National Forest							
Lincoln	9.7	9.7	21.7	1.1	-	-	[illegible]
Kootenai National Forest							
Rexford	5.0	5.0	19.4	-	-	-	19.4

[1]Timber is located partially on Lolo National Forest.
[2]Control plots.
[3]Prior to cutting.

Table 2.--*Gross board-foot volumes of trees 11 inches or greater per acre in initial plot stands by species*

Owner/Plot	Ponderosa pine	Lodgepole pine	Douglas-fir	Western larch	Total, all species
Anaconda Forest Products					
Lincoln	9,991	--	5,443	--	15,434
Fish Creek Forks	13,636	--	102	754	14,492
McCrea Park[1]	20,590	23	360	4,759	25,732
Longpre Cabins	12,550	--	499	245	13,294
Fishtrap Creek	14,353	--	646	--	14,999
Little Thompson River	14,852	557	20	45	15,474
North Fork Little Thompson River	15,616	464	451	787	17,318
Pleasant Valley	24,098	--	--	--	24,098
Jake Little Ranch	18,839	--	--	--	18,839
Lost Prairie	22,636	--	--	--	22,636
Lake McGregor	19,810	79	1,801	2,275	23,965
Glacier Park Co.					
Little Bitterroot River	15,800	--	2,250	--	18,050
St. Regis Paper Co.					
Loon Lake	16,722	--	--	--	16,722
Bitterroot National Forest					
Bear Creek Saddle	22,766	--	1,083	--	23,849
Overwhich Creek	25,198	24	8	--	25,230
Piquett Creek B[2]	17,078	--	2,136	--	19,214
D[2]	13,113	--	2,136	--	15,249
G[2]	14,888	--	2,136	--	17,024
J[2]	22,082	--	2,136	--	24,218
O[2]	15,354	--	2,136	--	17,490
Q[2]	15,749	--	2,136	--	17,885
C[3]	12,739	--	1,610	--	14,349
F[3]	17,245	--	1,129	--	18,374
H[3]	15,046	--	1,664	--	16,710
K[3]	15,429	--	884	--	16,313
L[3]	20,031	--	2,409	--	22,440
P[3]	14,052	--	2,106	--	16,158
A[3]	10,389	--	2,580	--	12,969
E[3]	21,129	--	2,167	--	23,296
I[3]	16,666	--	1,776	--	18,442
M[3]	19,161	--	1,532	--	20,693
N[3]	20,834	--	1,242	--	22,076
R[3]	13,716	--	1,057	--	14,773
Helena National Forest					
Lincoln	20,683	73	--	--	20,756
Kootenai National Forest					
Rexford	15,570	--	--	--	15,570

[1]Timber is located partially on Lolo National Forest.
[2]Control plots.
[3]Prior to cutting.

Pine Age Classes

Criteria used to select the ponderosa pine overstory [illegible] assured that the stands would contain a mean of at least 10,000 gross board feet per acre in pine trees classified by the Ponderosa Pine Tree Classification as mature or overmature. The initial age class inventory of the nearly 12,000 sawlog-size ponderosa pine trees in the plot stands showed that 73 percent of them were in these two age classes as shown by the following tabulation:

[illegible]	[illegible]	[illegible]
Young	466	[illegible]
Immature	2,735	22.9
Mature	[illegible]	[illegible]
Overmature	[illegible]	43.6
Total	11,946	100.0

JOHNSON, PHILIP C.

1972. Bark beetle risk in mature ponderosa pine forests in western Montana. USDA Forest Serv. Res. Pap. INT-119, 32 p.

Reports on results of a 20-year study on adaptability of the Ponderosa Pine Risk Rating System for identifying western pine beetle killing of mature trees in western Montana stands. Purpose was to ascertain whether sanitation-salvage cuttings could be used in such stands to control pine beetles with the same success as has been experienced in northeastern California and eastern Oregon.

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RISK RATINGS OF LIVING PONDEROSA PINE TREES

Procedures followed during the establishment of 553 acres of plots resulted in 11,946 sawlog-size ponderosa pine overstory trees being risk rated. The gross volume of these trees was 9,276,000 board feet. From this, it was possible to determine the number and volume of pine trees in each of the four ratings.

Distribution of Risk Rated Trees

Least abundant were trees rated Risk 1. These trees presumably are the least susceptible, or the most resistant, to attack by *Dendroctonus* bark beetles. They accounted for about 13 percent of the number and 8 percent of the volume, respectively, of the 11,946 risk rated pine trees (table 3). This paucity of low-risk trees also was discernible in each of the overstory stands of the 35 plots (table 4).

Trees rated Risk 2 (moderate) were by far the most abundant. Seventy-two percent of the number and volume of all the risk rated trees were in this category. Risk 2 trees, likewise, comprised a comparable proportion of risk rated trees in each of the plot stands (fig. 4).

Trees rated Risk 3 were considerably more abundant than those rated Risk 4 but, together, they made up 15 percent of the number and 20 percent of the volume, respectively, of the 11,946 risk rated trees (table 3). Risk 3 and Risk 4 trees, collectively, are the "high risk" trees of the risk rating system. They are the trees that sanitation-salvage cuttings are designed to remove from ponderosa pine stands to prevent the buildup in these stands of epidemic populations of bark beetles.

Table 3.--*Distribution by risk ratings of pooled sawlog-size ponderosa pine trees on 35 plots in western Montana* [1]

Risk ratings	Number of trees	Percent of total number	Gross volume (board feet)	Percent of total volume
1 (Low)	1,536 (2.8)	12.9	787,260 (1,424)	8.5
2 (Moderate)	8,628 (15.6)	72.2	6,640,970 (12,009)	71.6
3 (High)	1,533 (2.8)	12.8	1,583,390 (2,864)	17.1
4 (Very high)	249 (0.4)	2.1	264,740 (478)	2.8
Total	11,946 (21.6)	100.0	9,276,360 (16,775)	100.0

[1]Figures in parentheses represent per-acre values based on a combined total of 553 acres for the 35 plots.

Table 4.--*Number of ponderosa pine trees 11.1 inches d.b.h. or greater per acre in initial plot stands classified according to bark beetle risk ratings*

Owner/Plot	Risk rating 1	2	3	4
Anaconda Forest Products				
Lincoln	2.5	14.1	0.7	0.1
Fish Creek Forks	8.7	11.0	2.3	.4
McCrea Park[1]	2.7	11.8	2.3	.3
Longpre Cabins	9.9	23.5	3.0	.9
Fishtrap Creek	14.5	16.4	2.7	.2
Little Thompson River	4.7	19.4	2.2	.2
North Fork Little Thompson River	7.7	20.6	4.4	.9
Pleasant Valley	4.0	29.9	2.2	.5
Jake Little Ranch	4.3	20.0	3.0	.6
Lost Prairie	10.9	17.9	1.7	.2
Lake McGregor	6.7	27.0	2.1	.0
Glacier Park Co.				
Little Bitterroot River	4.8	17.9	4.8	1.4
St. Regis Paper Co.				
Loon Lake	14.5	11.3	1.5	.4
Helena National Forest				
Lincoln	5.6	12.7	1.7	.0
Kootenai National Forest				
Rexford	1.1	13.6	3.4	1.2
Bitterroot National Forest				
Bear Creek Saddle	1.5	14.0	4.6	0.5
Overwhich Creek	7.7	13.8	3.0	.6
Piquett Creek B[2]	.8	16.0	2.6	.2
D[2]	.5	12.8	2.7	.1
G[2]	1.5	17.3	1.9	.1
J[2]	1.4	21.0	3.6	.1
O[2]	1.3	11.7	1.6	.2
Q[2]	3.3	15.6	2.1	.1
C[3]	3.2	11.8	2.4	.1
F[3]	.4	17.1	2.3	.4
H[3]	1.1	13.9	2.6	.4
K[3]	.9	16.7	5.3	1.3
L[3]	.8	11.3	4.8	1.6
P[3]	2.0	11.7	1.5	.1
A[3]	.2	12.4	2.4	.2
E[3]	.7	18.6	3.5	.6
I[3]	1.3	15.7	2.2	.4
M[3]	.9	17.1	3.2	.7
N[3]	.2	13.7	2.6	.9
R[3]	2.6	11.3	3.2	.5

[1]Timber is located partially on Lolo National Forest.
[2]Control plots.
[3]Prior to cutting.

On the basis of the 553 acres of the 35 plots, Risk 3 and Risk 4 trees together averaged 3.2 trees and 3,342 board feet per acre. The mean per-acre volume of these high risk trees varied in each of the 35 plot stands, but it was less than 2,000 board feet in only eight of these stands (table 5).

Risk 3 and Risk 4 trees together represented 14.9 percent of the 11,946 mature ponderosa pine trees measured during the study; their total volume constituted 19.9 percent of all measured pine trees. These percentages, too, varied among the 35 plot stands (fig. 5).

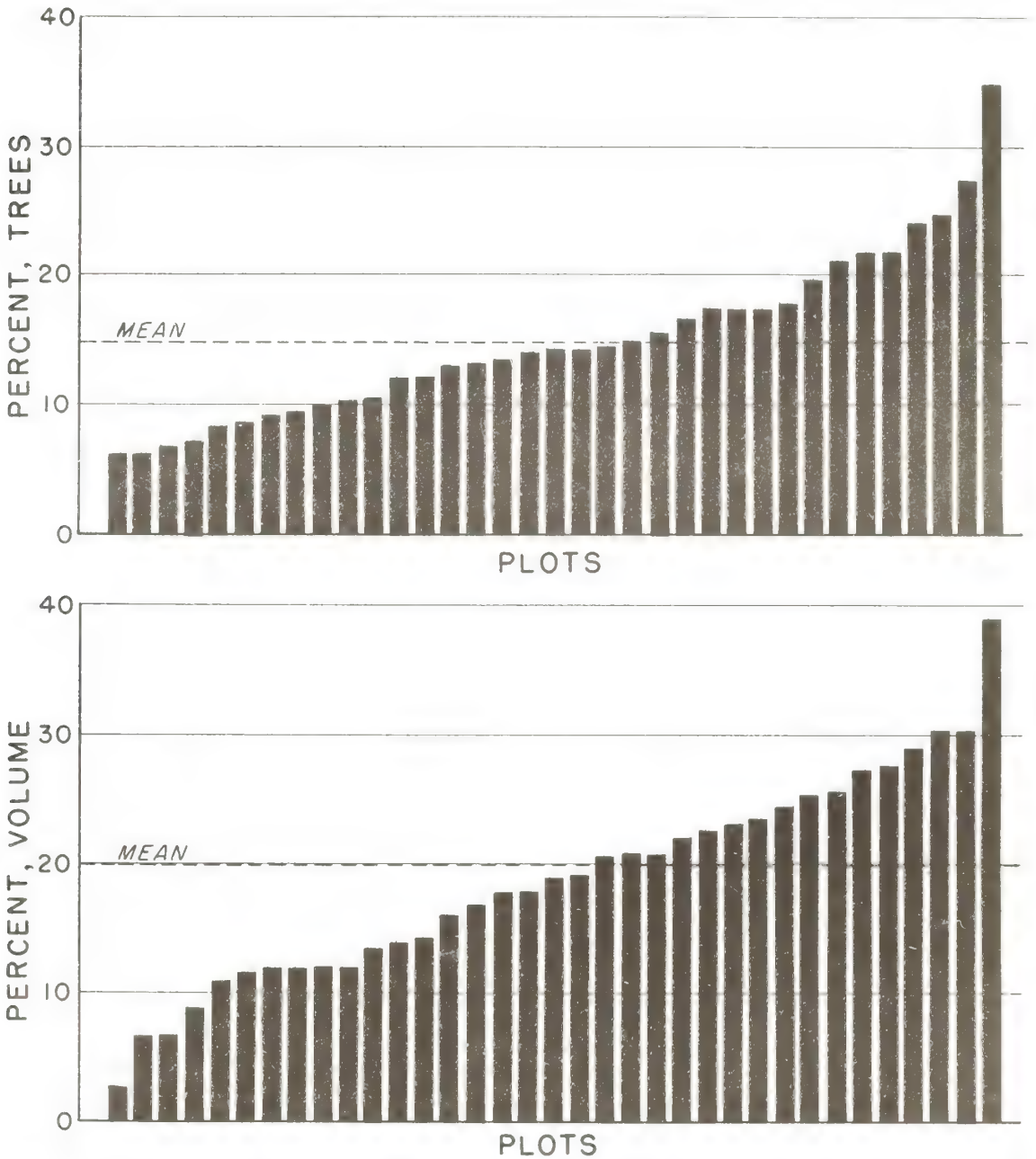

Figure 5.--Variation in the percentage of pooled Risk 3 and Risk 4 trees in overstory stands of mature ponderosa pine on 35 plots in western Montana. The horizontal position of the plots is not necessarily the same in the upper and lower histograms.

Table 5.--*Mean board-foot volume of ponderosa pine trees 11.1 inches d.b.h. or greater per acre in initial plot areas classified according to bark beetle risk ratings*

Owner/Plot	Risk Rating			
	1	2	3	4
Anaconda Forest Products				
Lincoln	1,493	8,240	230	28
Fish Creek Forks	1,467	8,720	3,046	403
McCrea Park[1]	5,417	12,933	2,070	170
Longpre Cabins	1,937	8,829	1,445	339
Fishtrap Creek	2,110	9,693	2,438	112
Little Thompson River	1,369	11,416	2,014	53
North Fork Little Thompson River	1,310	10,897	2,721	688
Pleasant Valley	2,722	19,787	1,383	206
Jake Little Ranch	1,932	12,589	5,057	1,261
Lost Prairie	5,209	14,369	2,631	427
Lake McGregor	2,694	14,842	2,256	18
Glacier Park Co.				
Little Bitterroot River	1,513	10,423	3,222	642
St. Regis Paper Co.				
Loon Lake	6,136	8,620	1,862	104
Helena National Forest				
Lincoln	4,116	14,050	2,517	0
Kootenai National Forest				
Rexford	916	11,718	2,150	790
Bitterroot National Forest				
Bear Creek Saddle	916	16,024	5,546	280
Overwhich Creek	7,318	15,150	2,574	156
Piquett Creek B[3]	726	13,121	2,877	354
D[3]	254	8,909	3,780	170
G[3]	1,114	12,006	1,665	103
J[3]	1,071	16,488	4,472	51
O[3]	2,028	11,494	1,632	200
Q[3]	1,768	12,076	1,876	29
C[4]	1,983	8,099	2,608	48
F[4]	156	14,356	2,309	424
H[4]	151	10,768	3,644	483
K[4]	263	10,519	3,579	1,067
L[4]	730	11,497	5,504	2,301
P[4]	2,027	10,765	1,096	164
A[4]	28	7,345	2,837	179
E[4]	270	16,063	4,276	520
I[4]	1,058	12,819	2,513	276
M[4]	673	14,272	3,119	1,097
N[4]	180	14,915	4,118	1,621
R[4]	1,980	8,509	2,678	549

[1]Timbered acreage shown on table 1.
[2]Timber is located partially on Lolo National Forest.
[3]Control plots.
[4]Prior to cutting.

Table 6.--*Relationship between the abundance of high risk ponderosa pine trees and some soil characteristics in western Montana*

Number of plots	Percentage of Risk 3 and Risk 4 trees in the stand	Soil fertility rating class[1]	Soil productivity site index[2]	Water-holding capacity[3]
				Inches
5	7-12	1	66-71	12-16
4	13-18	2	54-71	6-12
2	19-21	3	54-60	5-6
4	22-25	3-4	54	5-6

[1]Relative rating of soils between plots; based on chemical and physical properties of the soils and their ability to supply plant nutrients. Class 1, high; classes 2 and 3, moderate; class 4, low.

[2]A measure of productivity under specified management practices. Tree height at 100 years (Meyer 1938). Correlated with information from Cox and others (1960).

[3]As measured in top 5 feet of soil.

Risk Ratings and Soil Characteristics

The preliminary method of soil examination used by McConnell[8] on 15 of the plots in 1966 disclosed that the incidence of high risk pine trees in the sampled plot stands was associated with several soil characteristics. Increasing percentages of pooled Risk 3 and Risk 4 trees were closely related to (1) decreasing soil fertility rating classes, (2) soil productivity site classes, and (3) inches of water-holding capacity in the top 5 feet of soil (table 6).

A general relationship was indicated between the abundance of high risk trees and the following factors observed or measured in the preliminary soil examinations: (1) Soil depth to gravel-sand or bedrock; (2) texture of profile; (3) underlying soil material; and (4) related soil series.

No apparent relationship was indicated between the abundance of high risk trees and the following factors: (1) Depth to water table; (2) elevation, slope, or exposure; (3) landform; (4) mean annual precipitation or F-degree temperatures of the nearest meteorological station; (5) precipitation-evaporation transpiration index; or (6) windthrow and windthrow physiography.

Risk Ratings and Tree Growth Rates

The increment cores taken from basal bole sections of the 383 trees were measured for the years 1944 to 1953, the most recent 10-year growth period. The mean cumulative width of the annual rings for the period, 1944 to 1953, was calculated in inches for each core group on each plot. The value derived is expressed as the mean 10-year cumulative radial increment.

[8]Op. cit.

Table 7.--*Comparison of the mean 10-year cumulative radial increment between mature ponderosa pine trees of different risk ratings in western Montana*

Plot	Number of trees sampled	Mean increment		
		Risk 1 trees	Risk 2 trees	Risks 3 and 4 trees[1]
		Inch		
A	212	0.37	0.23	0.15
B	90	.43	.36	.19
C	38	.49	.35	.19
D	43	.43	.30	.20
Average		.43	.31	.18
Number of trees in Risk group(s)		143	168	72

[1]These two ratings were pooled for statistical analyses.

When compared with data reported by Spencer (1953), these means exhibited a progressive decline in value from trees rated Risk 1 to those of the pooled Risk 3 and Risk 4 trees (table 7). This statistically significant reduction in growth rates confirmed the poor vigor of trees rated Risk 3 and Risk 4. This reduction had been suspected because the risk rating system identifies trees having weakened or decadent crowns.

Mean Volumes of Risk Rated Trees

The mean gross volume of the 11,946 sawlog-size risk-rated trees was 776 board feet. The mean volume of Risk 1 and Risk 2 trees was less than this value; that of Risk 3 and Risk 4 trees exceeded it, as shown in the following tabulation:

Risk ratings	*Number of risk rated trees*	*Volume of risk rated trees (Board feet)*	*Mean volume per tree (Board feet)*
1 (Low)	1,536	787,260	512
2 (Moderate)	8,628	6,640,970	770
3 (High)	1,533	1,583,390	1,033
4 (Very high)	249	264,740	1,063
Total	11,946	9,276,360	776

CAUSES OF PINE TREE KILLING

The killing of mature ponderosa pine trees from several causes was measured on 22 plots that retained undisturbed virgin stands throughout the study. The timber stands on these plots were not subjected at any time to ground fires, flooding, or other environmental disturbances that would cause the death of ponderosa pine trees within 1 year or less.

Measurements from the 22 plots recorded the death during the study of 366 mature ponderosa pine trees having a combined volume of 308,810 board feet (table 8). They were killed by attacks of *Dendroctonus* bark beetles, lightning strikes, other cambium-feeding insects, windstorms, or unknown causes.

Similar measurements of ponderosa pine mortality from 13 other plots used for portions of the study are not reported here. The stands on these latter plots were lightly cut under several experimental tree selection systems soon after the plots were established. The cuttings were made to determine if such treatments could influence the postcutting rate of ponderosa pine tree killing by bark beetles or other quick-acting lethal agents.

The uprooting or lethal breaking of trees by windstorms proved to be the greatest source of mortality: 52 percent of the 366 trees killed on the plots were from this source (table 8). Such killing occurred on almost all the plots each year, but several plots were subjected to catastrophic tree killing from two or three windstorms of hurricane force that swept through parts of western Montana during the study. On two plots (Loon Lake and Jake Little Ranch), the damage was so great that the usefulness of these plots ceased after 4 and 7 years, respectively (table 9).

Table 8.--*Cause and amount of ponderosa pine tree mortality from 1948 through 1968 on 22 plots not subjected to sanitation-salvage cuttings*[1]

Cause of tree mortality	Total mortality		Mortality per acre per year	
	Trees	Board feet	Trees	Board feet
Bark beetles	132	103,360	0.020	15.5
Lightning	16	29,330	.003	5.5
Other insects[2]	18	9,080	.002	1.8
Unknown	11	15,790	.002	2.7
Windstorms	189	151,250	.026	21.4
Total	366	308,810	.053	46.9

[1]See table 9 for number of years of records form each plot.
[2]Principally, the pine engraver (*Ips pini*) and the California flatheaded borer (*Melanophila californica*).

The next greatest source of pine tree killing was infestation by bark beetles. It also was the most consistently occurring form of mortality in the plot stands year after year (fig. 6). Bark beetles accounted for the death of 132 pine trees (36 percent of all the trees killed during the study).

Of these 132 trees, 124 were killed by the western pine beetle *(Dendroctonus brevicomis)* and eight by the mountain pine beetle *(Dendroctonus ponderosae)*. None of the trees killed by *Dendroctonus* beetles had been previously top-killed by the pine engraver *(Ips pini)*, nor was this form of damage to mature ponderosa pine trees observed in the plot stands.

Systematic bole analyses to determine the insect species responsible for the death of these trees indicated that the trees were killed by low level populations of attacking pine beetles. Not only were the attacks per square foot of bole bark surface relatively few, but the areas of infested cambium occupied by developing broods of these insects were scattered and likewise small. This provided ample habitat for secondary cambium-feeding insects to subsequently infest these same trees. Consequently, relatively large proportions of the available bole cambium of beetle-killed trees were infested by *Ips emarginatus* (LeConte), *Ips plastographus* (LeConte), and by assorted wood-boring beetles of the families Buprestidae and Cerambycidae (Johnson 1967).

Lightning, other cambium-feeding insects, and unknown causes together made up about 12 percent of the trees killed (fig. 7). For the most part, the occurrence of tree killing from these causes was sporadic and unpredictable as to their locale and timing.

Table 9.--

Plot[1]	No. of years of record	Bark beetles		Lightning		Other insects		Unknown		All types		Total	
		No. of trees	Volume	No. of trees	Volume	No. of trees	Volume	No. of trees	Volume	No. of types	Volume	No. of types	Volume
Fish Creek Forks	17	3	7,620					1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
McGregor Park	17	3	[illegible]	1	[illegible]			1	1,100	[illegible]	[illegible]	[illegible]	[illegible]
Longpre Cabins	17	14	[illegible]							[illegible]	[illegible]	[illegible]	[illegible]
Fishtrap Creek	17	3	[illegible]			1	[illegible]					[illegible]	[illegible]
Little Thompson River	17	8	[illegible]	2	1,370	2	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
North Fork Little Thompson River	17	14	[illegible]			[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
Pleasant Valley	17	2	[illegible]							[illegible]	[illegible]	[illegible]	[illegible]
Lake Little Ranch	[illegible]	3	[illegible]									[illegible]	[illegible]
Lost Prairie	17	1	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]				
Lake McGregor	17	1	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Little Bitterroot River	17	9	[illegible]			3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Swan Lake	[illegible]	[illegible]	[illegible]			1	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
Lextord	20	3	[illegible]			[illegible]	[illegible]					[illegible]	[illegible]
Bear Creek Saddle	17	4	[illegible]									[illegible]	[illegible]
Swan River	17	1	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]
Lincoln	17	2	[illegible]	[illegible]	[illegible]							[illegible]	[illegible]
Liggett Creek B*	10	[illegible]	[illegible]	1	[illegible]							[illegible]	[illegible]
D*	10	3	[illegible]	1	[illegible]							[illegible]	[illegible]
G*	10	11	[illegible]	1	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J*	10	16	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
O*	10	[illegible]	[illegible]									[illegible]	[illegible]
Q*	10	[illegible]	[illegible]	1	[illegible]							[illegible]	[illegible]
Total		132	[illegible]	16	[illegible]	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Weighted means per acre year	11.2	[illegible]	13.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[1] See table 2 for timbered acreage.

[2] Approximately 25 percent from infestations of the [illegible].

[3] Principally from infestations of the pine engraver [illegible].

[4] Total: [illegible].

Figure 6.--Standing or fallen dead pine trees often are indisputable evidence of the severity of tree killing by the western pine beetle in past years throughout many old-growth ponderosa pine forests in western Montana. Loss of merchantable trees from even endemic populations of the pine beetle can be a significant cost factor in commercially managed ponderosa pine forests. It can be greater if nonpine tree species--such as Douglas-fir, shown here--swiftly usurp the ground surface under the former crown shadow of the dead pine trees, thus preventing establishment of often-desired seedlings of ponderosa pine.

Figure 7.--This mature ponderosa pine tree dying on a risk rating plot in the Bitterroot National Forest, Montana, was struck by lightning during the spring of 1964 and heavily infested soon after by two successive generations of the western pine beetle. While the tree might have survived the lightning strike, it could not have survived the excessively numerous attacks of the pine beetle. Ponderosa pine trees occasionally struck by lightning in western Montana are usually dominant, vigorous, low-risk trees presumably resistant to attacks of the pine beetle. Once they are struck by lightning, however, they become highly attractive for a year or two as a breeding habitat for the beetle.

RISK RATINGS OF BEETLE-KILLED PONDEROSA PINE TREES

Approximately three of every four of the 132 ponderosa pine trees killed by *Dendroctonus* bark beetles on the plots since the start of the study were either Risk 3 (high risk) or Risk 4 (very high risk) trees (see table 10). The proportion of the high risk trees (Risk 3 and Risk 4 together) among the total number of beetle-killed pine trees varied from plot to plot. In 20 of the 22 plots, however, high risk beetle-killed trees exceeded low risk beetle-killed trees (Risk 1 and Risk 2 together) both in their number and board-foot volume (table 11).

From the pooled data in table 10, it is evident that Risk 2 trees were almost as numerous as Risk 4 trees among all the trees killed by pine beetles on the plots. The 38 Risk 2 trees, however, came from a substrate that was 39 times larger than that from which the 40 Risk 4 trees came (table 3). This suggests that Risk 4 trees would be killed by pine beetles sooner than an equal number of Risk 2 trees.

Table 10.--*Distribution by risk ratings of ponderosa pine trees killed by bark beetles from 1948 through 1968 on 22 plots not subjected to sanitation-salvage cuttings*

Risk ratings	Trees		Volume	
	Number	*Percent*	*Board feet*	*Percent*
1 (Low)	1	0.8	220	0.2
2 (Moderate)	38	28.8	24,520	23.7
3 (High)	53	40.1	43,800	42.4
4 (Very high)	40	30.3	34,820	33.7
Total	132	100.0	103,360	100.0

Table 11.--*Distribution by risk ratings of ponderosa pine trees killed by bark beetles from 1948 through 1968 on 22 study plots not subjected to sanitation-salvage cuttings*

Plot[1]	Risk I (Low)		Risk II (Moderate)		Risk III (High)[2]		Risk IV (Very high)[2]		Total	
	No. of trees[3]	Volume[4]	No. of trees	Volume	No. of trees	Volume	No. of trees	Volume	No. of trees	Volume
		Bd.ft.		*Bd.ft.*		*Bd.ft.*		*Bd.ft.*		*Bd.ft.*
Fish Creek Forks					1	1,820	2	3,800	3	5,620
McCrea Park			1	2,290	1	980	1	420	3	3,690
Longpre Cabins			7	3,310	3	560	4	1,630	14	5,500
Fishtrap Creek			2	100	1	920	2	560	5	1,580
Little Thompson River			4	750	4	2,410			8	3,160
North Fork Little Thompson River			3	1,890	5	2,620	6	5,780	14	10,290
Pleasant Valley			1	760			1	420	2	1,180
Jake Little Ranch					1	340	2	6,730	3	7,070
Lost Prairie			1	1,910					1	1,910
Lake McGregor			1	50					1	50
Little Bitterroot River			3	2,070	2	1,820	4	2,450	9	6,340
Loon Lake	1	220	1	260	2	910	3	1,840	7	3,230
Rexford			1	480			2	1,200	3	1,680
Bear Creek Saddle					2	2,090	2	800	4	2,890
Overwhich Creek			2	1,720	1	420	1	860	4	3,000
Lincoln					2	4,530	1	1,390	3	5,920
Piquett Creek B[5]			3	420	2	900	1	980	6	2,300
D[5]			1	1,160	2	960			3	2,120
G[5]			2	1,940	5	4,820	4	3,690	11	10,450
J[5]			3	2,130	12	11,760	1	110	16	14,000
O[5]			1	1,640	3	3,910	2	1,340	6	6,890
Q[5]			1	1,640	4	2,030	1	820	6	4,490
Total	1(0.8)	220(0.2)	38(28.8)	24,520(23.7)	53(40.1)	43,800(42.4)	40(30.3)	34,820(33.7)	132(100)	103,360(100)

[1]See table 1 for timbered acreage and table 9 for years of record.
[2]Normally cut for bark beetle control in sanitation-salvage cuttings.
[3]Percent of total number of trees shown in parentheses.
[4]Percent of total volume shown in parentheses.
[5]Control plots.

Entomologists have used mortality ratios as a device to determine the relative susceptibility to beetle infestation of ponderosa pine trees in different tree classifications or risk ratings (Keen 1943; Keen and Miller 1960). The ratios are derived by dividing the percentage of trees killed in a given risk rating by the percentage of occurrence of all trees, living and dead, in this rating. Using data from 22 undisturbed study plots in table 5 and from table 10, mortality ratios indicate that Risk 3 trees are likely to be killed by bark beetles 2.77 times as often as the average tree in the plot stands and Risk 4 trees 22.47 times as often (table 12).

Table 12.--*Relative susceptibility of risk rated ponderosa pine trees to bark beetle infestation in western Montana as indicated by mortality ratios based on tree volumes for the period 1948-1968*

Risk ratings	Percentage of occurrence		Mortality ratios[1]
	Living and dead trees	Beetle-killed trees	
1 (Low)	11.7	0.2	0.02
2 (Moderate)	71.5	23.7	.33
3 (High)	15.3	42.4	2.77
4 (Very high)	1.5	33.7	22.47
3 and 4 combined	16.8	76.1	4.53

[1]Values greater than 1.00 indicate susceptibility to beetle attack; values less than 1.00 indicate resistance to beetle attack.

DISCUSSION AND CONCLUSIONS

An average loss of 15.5 board feet per acre per year from attacks of *Dendroctonus* bark beetles underscored the endemic nature of these insect pests throughout the duration of the study. At this low level of timber losses, the "bark beetle problem" must certainly not have been of much concern to forest managers in western Montana during the period from 1948 through 1968. Furthermore, the almost continuous endemic infestations did not contribute as much as they might have to a meaningful test of the Ponderosa Pine Risk Rating System here. This would have required a much greater quantity of beetle-killed ponderosa pine trees than the sluggish infestations produced for the study.

Some questions, therefore, might well be asked. Will *Dendroctonus* beetles, for instance, ever be a problem in the management of mature ponderosa pine stands in western Montana or, more broadly, throughout the northern Rocky Mountain States west of the Continental Divide?[9] And, if so, can the risk rating system help to alleviate it?

To answer the first question, records of forest insect surveys in the northern Rockies document past outbreaks of the western pine beetle and the mountain pine beetle in mature stands of ponderosa pine. True, these outbreaks have not produced such devastating tree killing as have outbreaks of bark beetles in parts of the Pacific Coast States where, in 1956 in one outbreak area, pine beetles killed an average of 208 board feet of ponderosa pine per acre (Wickman and Eaton 1962). Notwithstanding, the more severe outbreaks of bark beetles in the northern Rockies have produced tree killing that caused depletion of ponderosa pine stands and interfered with orderly forest management planning and operations. Severe outbreaks of bark beetles will undoubtedly occur again in the northern Rockies as long as there are stands of mature ponderosa pine trees and as environmental conditions might change to encourage buildup of beetle populations to epizootic levels.

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[9]The western pine beetle is not found east of the Continental Divide. East of the Divide the mountain pine beetle becomes one of the primary tree-killing pests of the Rocky Mountain form of ponderosa pine, *Pinus ponderosa* var. *scopulorum* Engelmann. The ecology of this latter pest-host relationship is entirely distinct from that being reported here.

It appears likely that forests of mature ponderosa pine will be present for many years; some will include remnants, perhaps, of today's old-growth pine stands. Young pine stands will continue to mature, most assuredly, under increasingly intensive management. Segments of today's mature ponderosa pine stands are being placed in more or less reserved status in some multiple use zones as a result of the pressures exerted by a growing outdoor recreation-oriented public. These pressures are already forcing consideration of more selective cutting practices that tend to delay harvest cuttings in commercial ponderosa pine stands (Curtis and Wilson 1958).

The threat of bark beetle outbreaks in western Montana's existing forests of mature ponderosa pine is already indicated by appreciable numbers and volumes of high risk pine trees. The possibility exists that even more high risk trees might develop in some stands as the pine overstory competes for soil nutrients and moisture with increasing numbers of dense understory stands of more tolerant species (fig. 3).

As to the second question, even the meager data produced by the risk rating study point to a recognizable ability of the risk rating system to identify pine trees variously susceptible to lethal attacks of bark beetles in western Montana, if not generally throughout the northern Rocky Mountains. Assuming this capability, the rating system can do here what it has done elsewhere:

1. Identify individual pine trees susceptible or resistant in varying degrees to beetle attack.

2. Assess the risk, or hazard, of whole pine stands from the threat of beetle-caused depletion, or from the likelihood of these stands serving as breeding habitats that may support rapidly expanding beetle populations (Johnson 1949, 1951).

3. Assist forest managers to formulate plans to counter the threat of beetle depredations by giving priority for harvest cuttings or stand improvement treatments to stands with the highest beetle hazard.

4. Provide the detailed basis for sanitation-salvage cuttings to beetleproof pine stands suspected of being unusually susceptible to damage from bark beetle outbreaks (Johnson 1968).

The study has provided information on the abundance of high risk trees in a variety of pine stands. For example, it has shown that most of the stands sampled had 15 percent or more of their volume in high risk trees. From results of this study and experience gained elsewhere, we believe that this percentage figure represents an arbitrary but realistic demarcation between ponderosa pine stands that are either resistant to serious beetle attacks (those with less than 15 percent of their volumes in high risk trees) or acutely susceptible to them (stands with more than 15 percent of their volumes in high risk trees).

Like those of other similar studies, the results of this study should allay the fears of some foresters and timber operators that sanitation-salvage cuttings are universally uneconomical. Finally, economic-oriented studies have shown that harvesting of only high risk trees can be profitable and that the quality of timber removed is as good or better than that of the stand as a whole. It can be argued, of course, that some sanitation-salvage cuttings would not be economical.

In conclusion, we believe the study has provided foresters in this region with a workable basis for coping with a potentially serious insect problem--a basis soundly rooted in good silvicultural practice and responsive to the public's growing concern for operating techniques that exhibit full consideration for the total forest environment.

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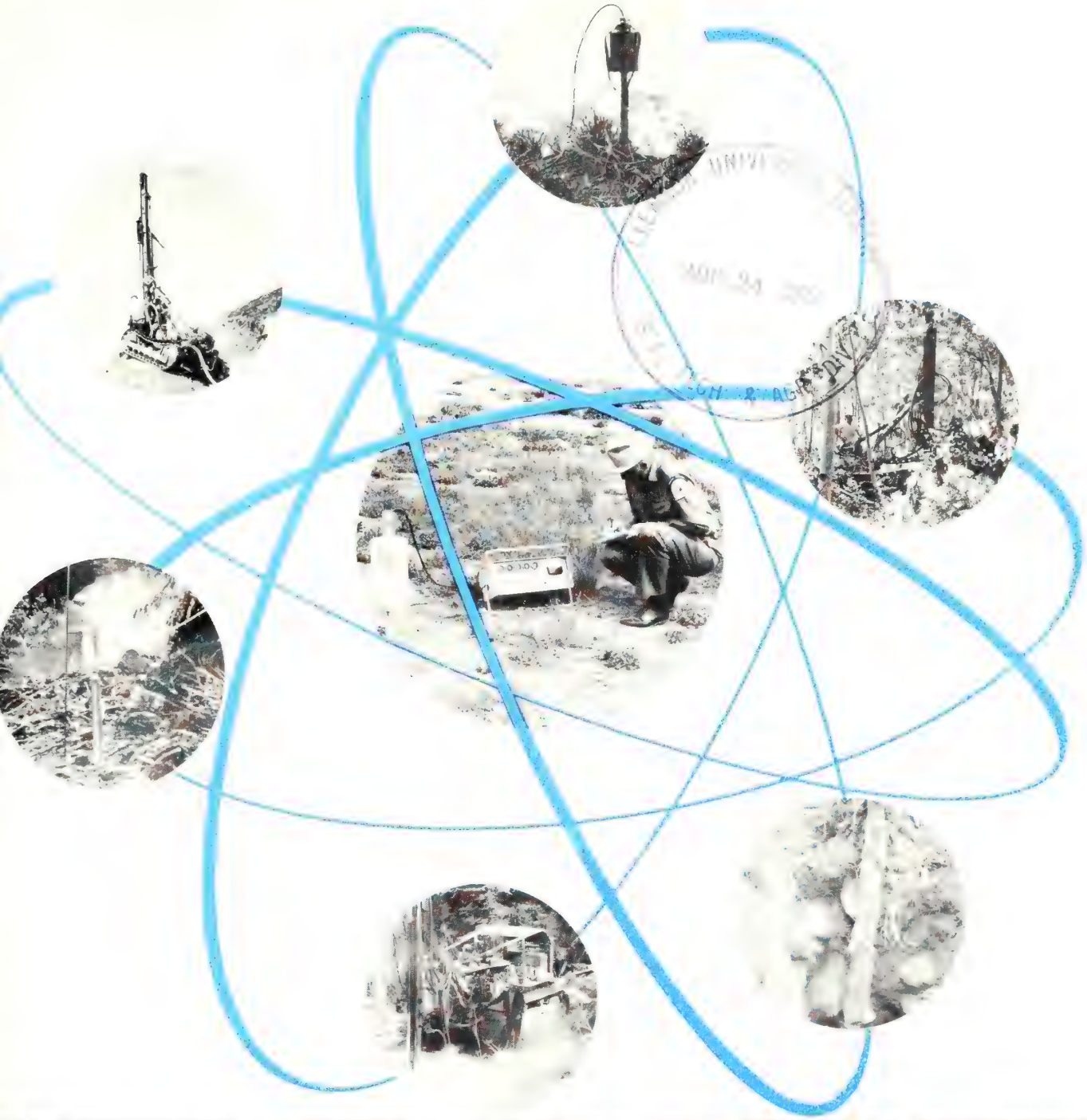

EFFECTS OF AIR GAPS AND SATURATED VOIDS ON ACCURACY OF NEUTRON MOISTURE MEASUREMENTS

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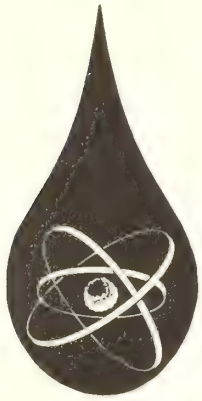

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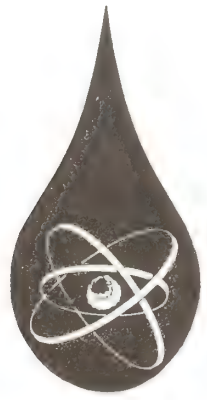

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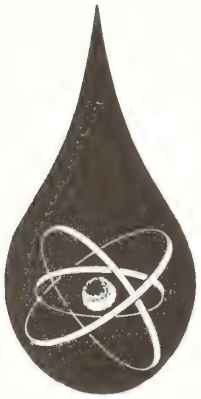

ABSTRACT

The effects of voids on the accuracy of neutron soil moisture measurements in coarse and fine sand were investigated utilizing two 25-cubic-foot plastic tanks. Test voids 3 inches and 6 inches in diameter and 10 inches long were cut from aluminum tubing and fastened to the neutron access tube in each tank. Voids in the control tank were filled with sand; those in the test tank were left empty. The amount of water which was added or subtracted was measured by weighing each tank. The difference in neutron measurements between the two tanks with the water at a given level measures the effects of the voids.

A maximum error of +55 percent moisture by volume was caused by the large void in coarse sand with the void saturated; with the void drained, the error was -12.3 percent moisture. Errors in fine sand were slightly less than those in coarse sand; and errors due to the small void were about one-third the magnitude of errors due to the large void. Graphs were developed for use in estimating the size of voids adjacent to access tubes and in calculating the probable magnitude of measurement errors due to these voids when using field data.

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INTRODUCTION

The neutron method of measuring soil moisture is widely accepted by hydrologists and soil scientists because the method can be fast, easily performed, and accurate. Accuracy is due primarily to the large volume of soil sampled, nevertheless it is essential that the sample be truly representative of the soil within the measured zone. If a soil void is adjacent to an access tube an error in measurement will result. The magnitude of the error is a function of the size and shape of the void as well as the volume of water within the void. Soil voids, due primarily to poor installation techniques, cause the greatest errors in neutron moisture measurements.

Many installation techniques will give satisfactory access tube installation in rock-free soils. However, in rocky wildland soils, special access tube installation procedures must be used to prevent voids between the soil and the tube (Richardson 1966). Unfortunately, literature that pertains specifically to the use of neutron meters in wildland soils is scarce; furthermore, literature dealing with the effect of voids on neutron moisture measurements is almost non-existent. Koshi (1966) tested various methods for drilling access holes in rocky soils and concluded that the holes must be drilled oversized to compensate for irregularities in the dimensions of the drilled hole. These holes were then backfilled with screened soil to remove any air gaps in the soil next to the access tube. Koshi also tested the effect of 1/8 inch to 3/8 inch air gaps next to access tubes installed in loamy soil and concluded that there was no effect. Troxler (1963) has suggested that 0.15 inch is the maximum air gap that can be tolerated without error.

If the soil profile never becomes saturated, then the effect of small air gaps is negligible. If the soil moisture regime is such that the ground water level fluctuates seasonally, then a small air gap next to the access tube introduces a small error in the summer when the soil is relatively dry. However, this fluctuation causes an unknown but much larger error when the water table rises and saturates a soil void (Burroughs 1967). In a study of soil moisture on wildland soils, Burroughs concluded that backfilling cannot be relied upon completely to fill all voids left by the installation process. Another conclusion was that the first indication of a serious void problem occurs when the void becomes saturated. Abnormally low neutron counts ca not be taken as prima facie evidence of a large air filled void. Koshi (1966) showed that a large rock next to the access tube may also cause a drop in count rate.

This paper describes a laboratory study of the error caused by voids adjacent to access tubes in a uniform porous medium when the soil moisture content changes from a fully saturated to a drained condition. The objectives are to define quantitatively the neutron errors so that scientists may have guides to detect the presence of voids and estimate the magnitude of the error associated with them.

METHODS AND PROCEDURES

The controlled conditions implicit in a laboratory study of the effects of voids on accuracy of neutron soil moisture measurements require that:

1. The volume of the porous medium be large enough to model a natural soil of infinite lateral extent.
2. The porous medium have a constant density throughout.
3. There be a reliable method for measuring the depth to the water table within the porous medium.
4. There be a reliable method for measuring the amount of water stored within the porous medium.

The effects of voids were measured within two 25-cubic foot plastic tanks; one tank served as a control, and the other tank was used for tests (fig. 1). Each tank had walls 0.50 inch thick and was 67-1/2 inches deep and 29 inches in diameter (inside dimensions). These dimensions were selected because a study by Marston (1965) showed that a radius of approximately 14 inches in drained soil is sufficient to contain the sphere of influence for a neutron soil moisture meter for readings taken at depths greater than 12 inches. In our study, a tank radius of 14-1/2 inches was considered to represent a volume of infinite lateral extent. A concave steel bottom equipped with a strainer and drain was fastened to each tank. A steel lid with a 2-inch hole to accommodate an aluminum soil moisture access tube was placed over the tank to prevent evaporation of water from the interior. Eight steel tension rods were spaced equally around the tank to clamp the top and bottom securely. A manometer made of plastic

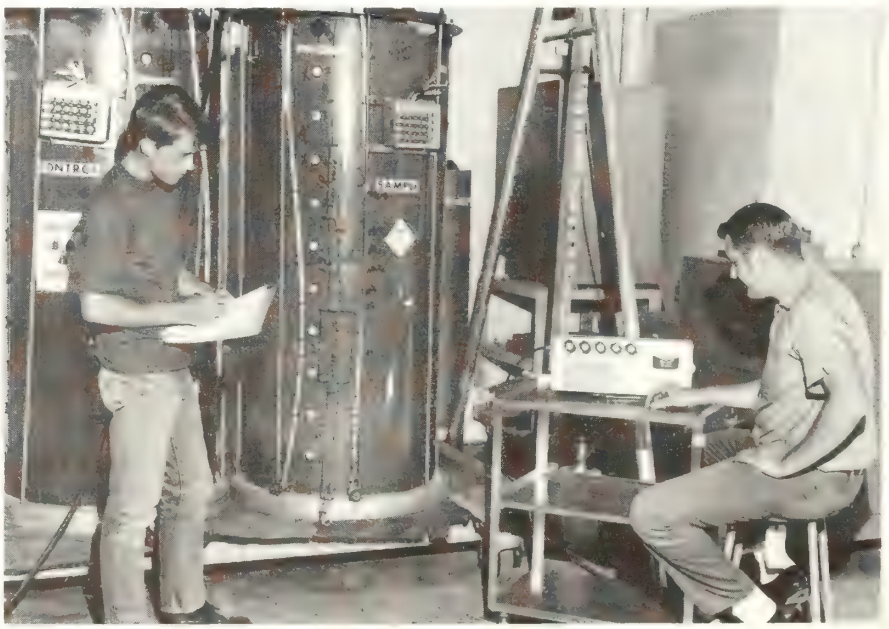

Figure 1. — Measurement of the effects of voids were made within two 25-cubic-foot plastic tanks. The sample tank contained built-in "voids" while the control tank had none.

pipe was threaded into the wall of the tank 1 inch above the bottom to indicate the level of the free water surface within the tank.

Forty holes 1-1/8 inches in diameter, and arranged in four vertical rows of 10 holes each, were drilled through the walls of each tank to check bulk density of the porous medium. These vertical rows were spaced equally around the tank and the holes within each row were spaced equally from top to bottom. The holes were sealed by expanding plugs made from black rubber stoppers having washers on each face and pierced by bolts. The plugs were compressed and expanded when the bolts were tightened.

The dimensions for the test voids were selected after an examination of field data from six access tubes. These tubes had been installed 6 feet deep and showed an extremely large seasonal fluctuation in soil moisture. Three of the tubes yielded neutron counts that seemed "reasonable," i.e., percent moisture by volume did not exceed soil pore space when soil was saturated. The remaining three tubes yielded questionable data, i.e., data indicating that the percent moisture by volume exceeded the pore space of the soil.

Castings were made of the access holes. Before this could be done, the rubber stoppers sealing the bottoms of the access tubes had to be removed. Cement was poured into the tubes and 3/8-inch reinforcing rods were used to work the mortar gently out the bottom of the tubes. As the cement flowed out into each of the access holes, the access tube was raised slowly and the reinforcing rod was left in the hole. When the access hole was filled completely with cement, the access tube was removed; and the cement was allowed to harden for 2 weeks. Then the castings were excavated (fig. 2) and measured. The three access holes yielding questionable data had voids, as determined by the castings, that ranged in size from 3 to 6 inches in diameter and up to 10 inches long.

The small and large test voids were made from 10-inch lengths of 3- and 6-inch-diameter aluminum irrigation pipe having wall thicknesses of 0.010-inch. These test voids represented two symmetrical voids with 1/2- and 2-inch annular space around the access tube (fig. 3).

A heavy pipe frame was erected in the laboratory to support an "I" beam which acted as a track for a rolling carriage that carried a hydraulic cylinder. Four lifting bars were attached to the top of each tank. When the hydraulic cylinder was attached to the lifting bars a small hydraulic hand pump was used to actuate the cylinder and lift the tank for weighing.

A coarse sand and a fine sand were used as the porous mediums for the study. Of the

Figure 2. — Access tube castings were excavated for shipment to laboratory. Some of the six castings showed voids up to 6 inches in diameter and 10 inches long.

Figure 3. — The left tank has been filled with sand. The small and large "voids" can be seen in the right tank. Manometers are mounted on the front of each tank. Plugs in the sides of tanks provide access for obtaining density and moisture samples.

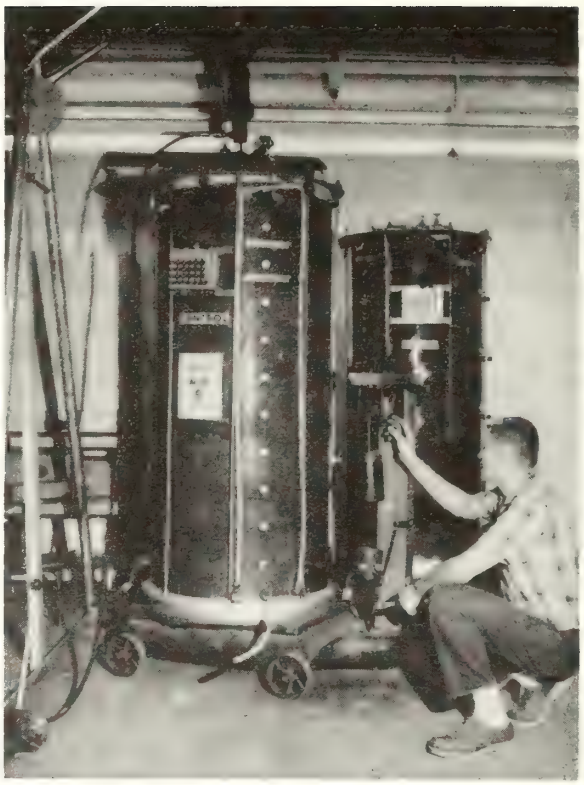

Figure 4. — An "I" beam, supported by steel "A" frames, serves as a track for a hoist used to lift tanks for weighing. Each tank was weighed while dry, after each change in water level, and at saturation.

coarse sand, 99 percent passed a #16 Tyler screen (1.00 mm.) and not more than 1.47 percent passed a #32 Tyler screen (0.500 mm.). Of the fine sand, 99 percent passed a #32 Tyler screen and only 18.73 percent passed a #60 Tyler screen (0.250 mm.) Before the tanks were filled with sand, the access tubes were centered in the tanks. Coarse sand was released from an overhead hopper through a hose in such a way that the particles had a constant fall distance and constant initial velocity to assure a constant bulk density.[1] When the level of sand in the tank reached 18 inches above the bottom, the large 6-inch-diameter void tube was slipped down over the access tube and allowed to rest on the sand. Pouring was resumed until there were 13-1/2 inches of sand over the top of the large void. Then the small 3-inch diameter void was slipped onto the access tube and filling with sand continued until there were 14 inches of sand over the small void and the sand was 2 inches from the top of the tank. This procedure was used to fill both tanks; however, in the control tank the test voids were filled with sand before the top of the void was attached. The only difference between the two tanks was that the test (sample) tank had empty voids and the control tank had voids filled with sand.

The tanks were positioned under the pipe frame and weighed (fig. 4) to determine the dry weight of sand in each tank. A hose was attached to the drain on the bottom of each tank and the tank was slowly filled with water from the bottom. It was then drained and refilled to remove all air from the sand. Each tank was reweighed when filled so that the total weight of water in the sand could be calculated.

[1] *Unpublished data in files of the Forestry Sciences Laboratory, Logan, Utah.*

A Troxler neutron soil moisture meter was used to measure the moisture content at predetermined depths in each tank under conditions of changing water levels. Thirteen water levels, measured in inches from the surface of the sand, were selected for this study (fig. 5). A one-minute counting period (Merriam 1962) was used at each of these 13 water levels. The center of measurement for the probe was assumed to be the center of the detector tube. After a set of 13 one-minute counts, the water level was lowered or raised to the next water level and the neutron measurements were repeated at all 13 water levels. Each set of readings was bounded by a set of 5 one-minute standard counts. The water which drained from the tank when the water level was lowered to the next stage was collected, measured, and compared with the weight of the tank before and after the change in water level. When the neutron measurements were completed on one tank (i.e., from a saturated to a drained condition), the process was repeated on the second tank. After all neutron measurements were completed, a series of bulk density samples were taken; the tanks were emptied and refilled with the fine sand.

Three sets of bulk density measurements were made in each of the two tanks: (1) small (142 cc.) gravimetric samples were taken through the side of the tank; (2) measurements were made with a Troxler depth-density gage; and (3) large (6,300 cc.) gravimetric samples were taken adjacent to each void when the tanks were emptied.

The small sampler consisted of a length of stainless steel conduit having an inside diameter of 1.05 inches; it was machined on the outside to a 1.12-inch diameter and had a flange acting as a stop to allow the sampler to penetrate 10 inches into the sand. After the tank had drained for 24 hours, a plug was removed from a sampling hole, and the small sampler was inserted. The 142-cc. sample was withdrawn, emptied into a can, weighed, and placed in an oven for drying and reweighing. As soon as the sampler was emptied, the sand was replaced by a sample drawn from a container of damp sand filled to the same bulk density from the overhead hopper. The replacement was inserted into the tank and held in place by a wooden plunger while the sampler was withdrawn and the rubber plug was replaced.

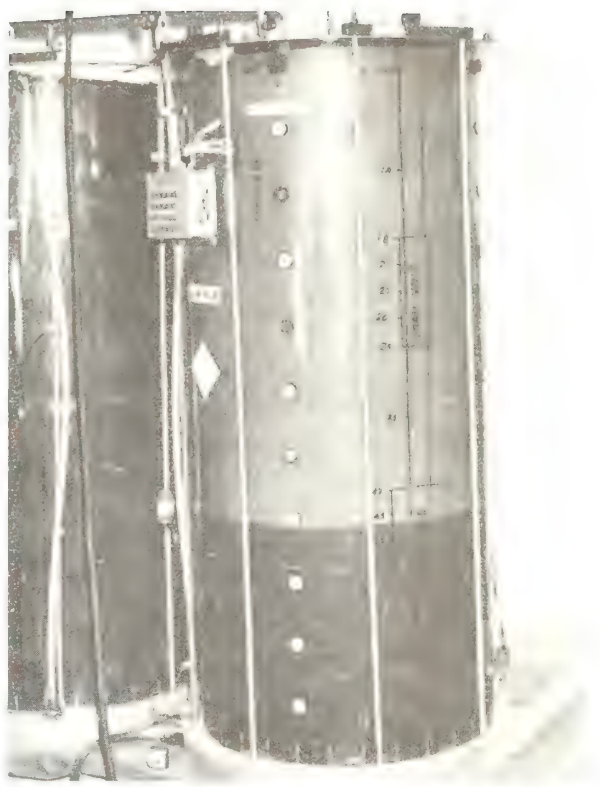

Figure 5. — Darker portion of tank on right is caused by rising water. Drawing on side of tank shows size and location of the small void and the large void within the tank. Numbers are in inches, measured from the surface of the medium.

The second set of samples was taken by lowering the Troxler depth-density gage into the access tube and measuring at each of the 13 levels.

The large gravimetric samples were taken at four levels in each tank. The first sample was taken after 4 inches of sand had been removed from the tank. The sampler was forced into the sand, the surrounding sand was removed, a piece of sheet metal was inserted under the sample, and the sample was removed from the tank; the sample was weighed, dried, and then reweighed. Another sample was taken between the small void and the wall of the tank; the center of the sample was on a level with the center of the void. A third sample was taken on a level corresponding to the center of the tank, and a fourth sample was taken opposite the large void.

RESULTS

Table 1 shows the bulk density of the two types of porous media as determined by the four methods: (1) large gravimetric sample; (2) small gravimetric samples; (3) the Troxler density probe; and (4) the ratio of the tank weight with dry sand to the volume of the tank occupied by the porous medium. This table shows that there is negligible difference in bulk density between the two tanks.

Most calibration curves show a linear relationship between neutron counts and percent moisture from zero to about 45 percent. A linear extrapolation of the calibration curve beyond 45 percent is not accurate because there is a curvilinear relationship between neutron counts and percent moisture beyond this point. For this study the factory furnished the authors with a calibrated curve used to convert neutron measurements to percent moisture by volume (fig. 6). Data from the control tank and the sample tank for a given water level were plotted on a master graph with depth of measurement on the ordinate and moisture content on the abscissa. An examination of the master graphs for each water level showed that the voids were far enough apart on the access tube to prevent an overlap in effects. Therefore, each master graph was redrawn as two graphs: one for data from the two tanks for depths of measurement which bracketed the small void; and another graph for data that bracketed the large void. Data points were connected to form two smooth curves which represent the soil moisture content at any depth in both the control tank and the sample tank when the water level was at a given depth. The effect of the void

Table 1. — A comparison of bulk density (in lb./ft.^{3}) in each tank for coarse and find sand as determined by four methods

	Small sample	Large sample	Troxler density probe	Tank wt./vol.
		COARSE SAND		
Control tank	98.9	99.8	101.5	99.9
Sample tank	99.2	99.6	100.2	99.9
		FINE SAND		
Control tank	101.6	100.9	([1])	102.4
Sample tank	100.9	101.3	([1])	101.7

[1] *The Troxler density probe was not available for measurements in the fine material.*

on neutron measurements made at a given depth was the difference, measured horizontally, between the two curves. This difference is referred to as measurement error and is expressed in percent moisture by volume.

Measurement errors were determined for each inch of depth for each graph and were plotted on total error graphs as the horizontal deviation from a vertical axis (figs. 7 through 10). The area under the error curve is the summation of the products of each measurement error and the inch of depth which each represents. Total error can be thought of as the total error in measurement (in inches of water) if neutron measurements had been made at each inch through the zone of influence around each void. The purpose of the computation of total error is to quantify the relative difference in the effect of a void as the water level changes.

Small Void--Coarse Sand

Figure 7A shows the results of measurements from the two tanks when the water levels were near the tops of the tanks; i.e., the area around the small void is saturated completely. The error in measurement at 24 inches below the surface was +17.5 percent by volume calculated by subtracting 45.0 percent for the control tank from 62.5 percent for the sample tank. From the surface of the sand down to a depth of 13 inches there is no measurement error due to the void. If readings were to be taken at each inch from 13 inches to 33 inches, the total error would be +1.86 inches.

Figure 7B shows the two curves when the water level had dropped to 18.75 inches below the surface. The void was still saturated and

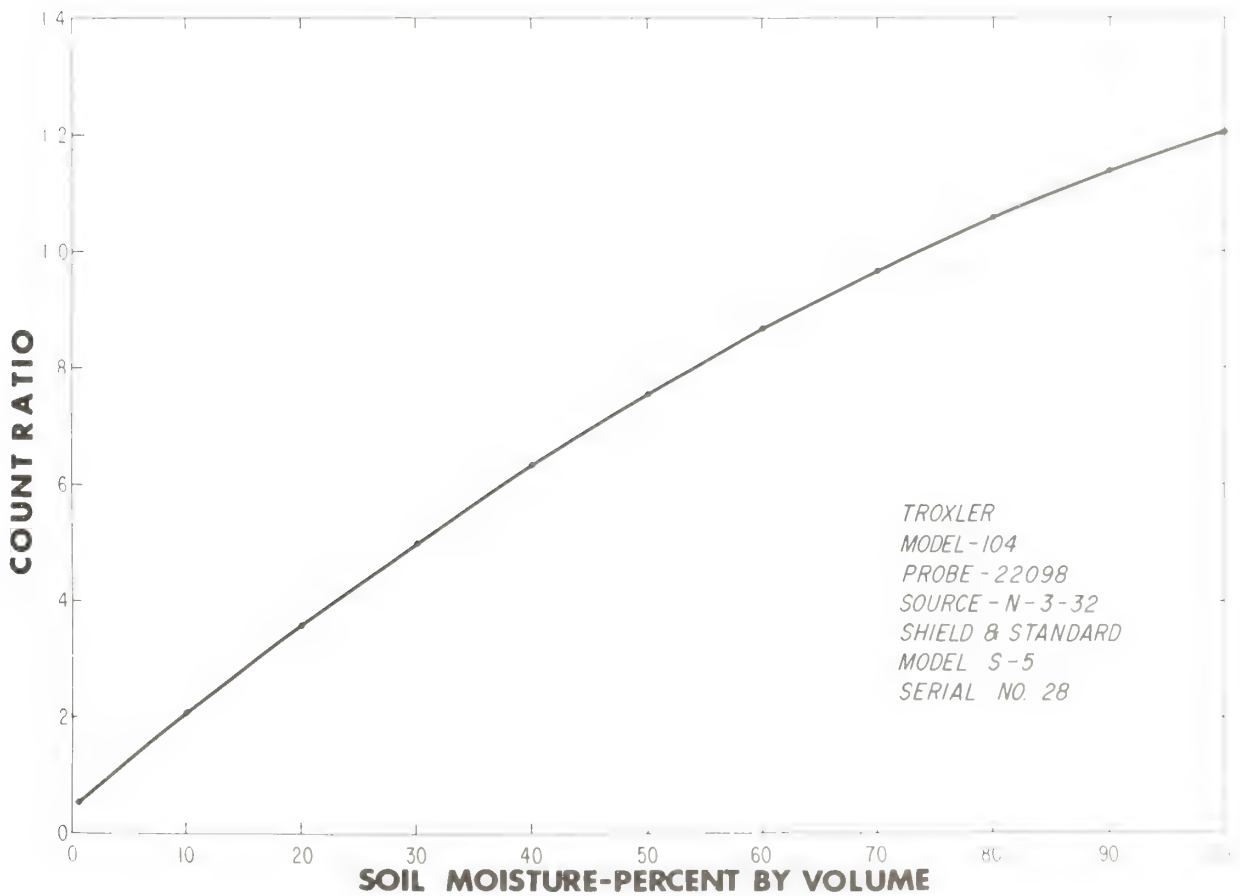

Figure 6. — Troxler calibration curve for a model 104 probe.

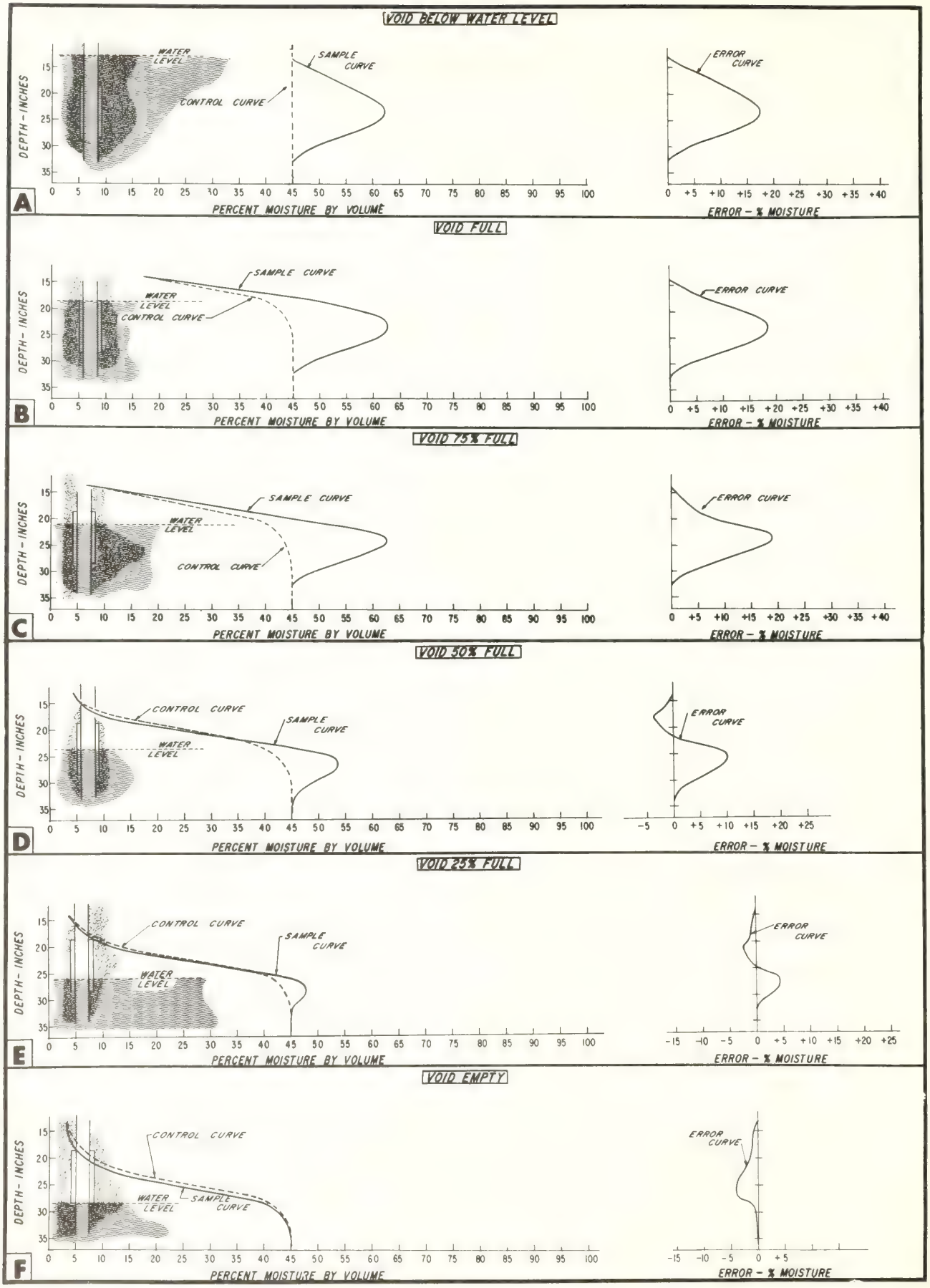

Figure 7. – The variation in neutron moisture measurements between control and sample tanks containing small voids is shown. Measurements were made using coarse sand as the porous medium with the water level changing with respect to the void.

the water level was at the top of the void. As the neutron source neared the water level, the moisture content increased linearly until the center of measurement reached the water level; then the true soil moisture content approached the saturated value of 45 percent (maximum pore volume) asymptotically. Thus, the neutron meter indicated that the water level (total saturation) was at 26 inches depth when the water level was actually at 18-3/4 inches depth. By comparing the control curve and the sample curve, it can be seen that there was no error when the probe was at 14 inches, but the positive error increased with depth as the fully saturated void strongly influenced the neutron measurement in the sample tank. The maximum positive error was +18.5 percent, or slightly higher than when the water level was at the surface of the medium. The reason for this was that the peak reading in the sample tank had not changed while the curve for the control tank flexed sharply under the effect of the lowered water table.

In figure 7C, the water level was down to 21-1/4 inches, and the void was three-fourths full. At 14 inches depth, there was no measurement error; at 23-3/4 inches depth, the measurement was +19.2 percent. The increase in positive error, when the void was not fully saturated, was caused by the lowering of the rounded portion of the control curve to a point opposite the peak in the sample curve. The total measurement error was +1.38 inches.

Figure 7D shows the situation when the water level was 23-3/4 inches below the surface and the void was half full. With the center of measurement at 14 inches depth, the source was on a level with the upper half of the void which acted as a large air gap and gave a negative measurement error. The water level just below the source acted to reduce the magnitude of the negative error. The total measurement error from 14 inches to 33 inches was +0.50 inch of water and was the algebraic sum of the negative and positive measurement errors.

Figures 7E and 7F show the reduction in the amount of positive measurement error as the water level dropped. When the void was entirely empty, the largest measurement error was -4.1 percent. The total measurement error was -0.35 inch.

Large Void--Coarse Sand

The measurement error caused by the large void was very similar in shape to that of the small void except that the magnitude of the errors was quite different. Figure 8A shows the water level above the large void, which means the medium surrounding the large void was saturated completely. The maximum measurement error was +55.0 percent moisture by volume, and the total measurement error through the void was +5.64 inches. In figure 8B the water level was 42 inches below the surface and at the top of the large void; the soil moisture curve for the control tank showed the same sharply reflexed shape as seen in figure 7B for the small void. The maximum measurement error was +55.0 percent and the total error was +5.52 inches. Figures 8C through 8F show the progressive reduction of the positive error and the increase of the negative error as the water-filled void became an air gap.

Small Void--Fine Sand

Figure 9A shows the results of measurements from the two tanks when the small void was fully saturated. The error in measurement with the probe at 24 inches below the surface was +16.5 percent by volume. The total measurement error from 13 inches to 33 inches below the surface was +1.54 inches of water.

Figure 9B shows the two curves with the water level dropped to 18-3/4 inches below the surface; the water level was at the top of the void. The maximum measurement error was +16.6 percent by volume with a total measurement error of +1.42 inches of water from 16 inches below the surface to 33 inches below the surface.

Figure 9D shows the two curves with the small void half full of water, a condition which produced only a small amount of negative measurement error. The maximum negative error was -3.1 percent moisture by volume, and the maximum positive error was +8.4 percent by volume. The total measurement error for the void was +0.32 inch of water.

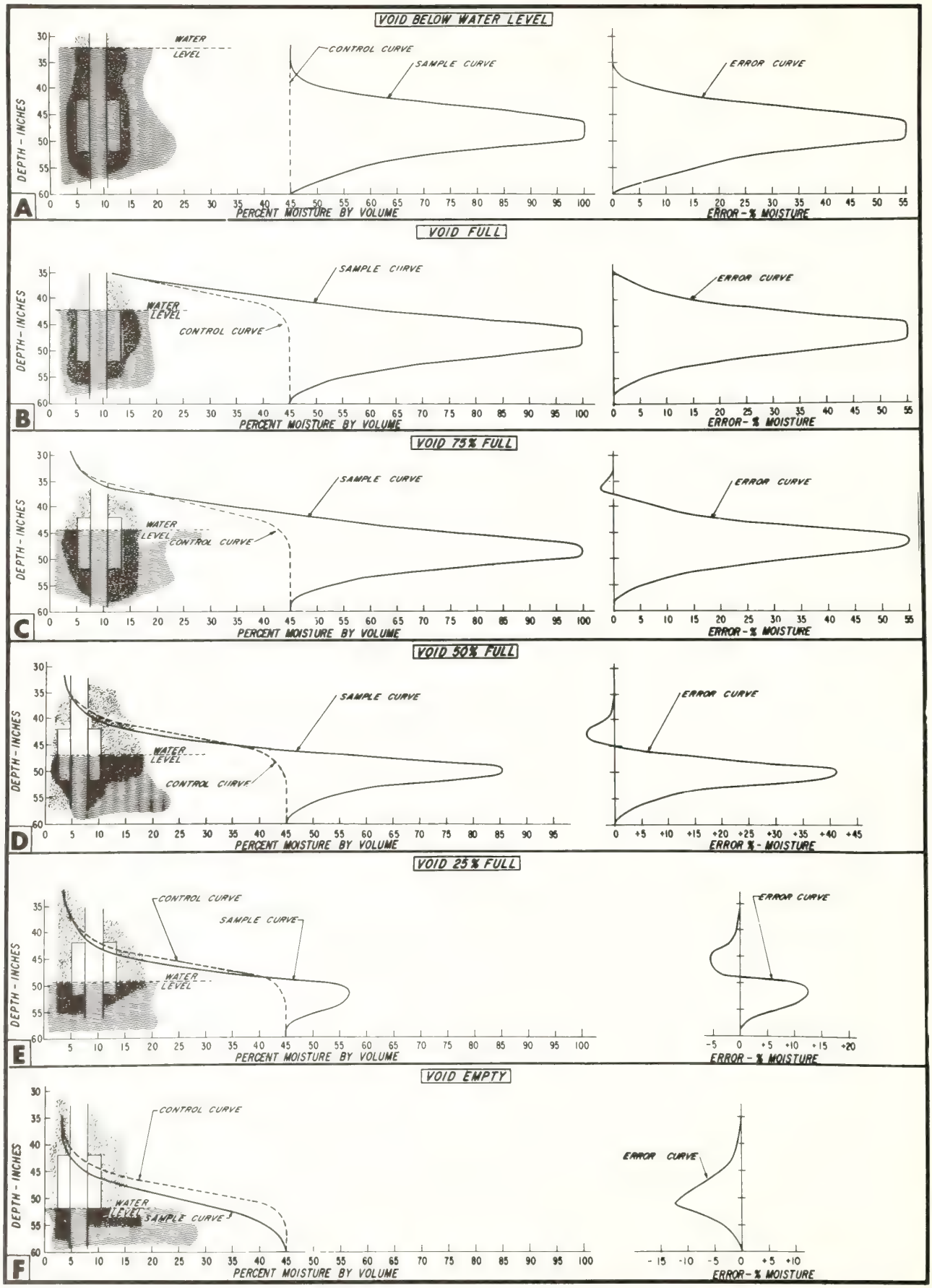

Figure 8. – The variation in neutron moisture measurements between control and sample tanks containing large voids is shown. Measurements were made using coarse sand as the porous medium when the water level was changing with respect to the void.

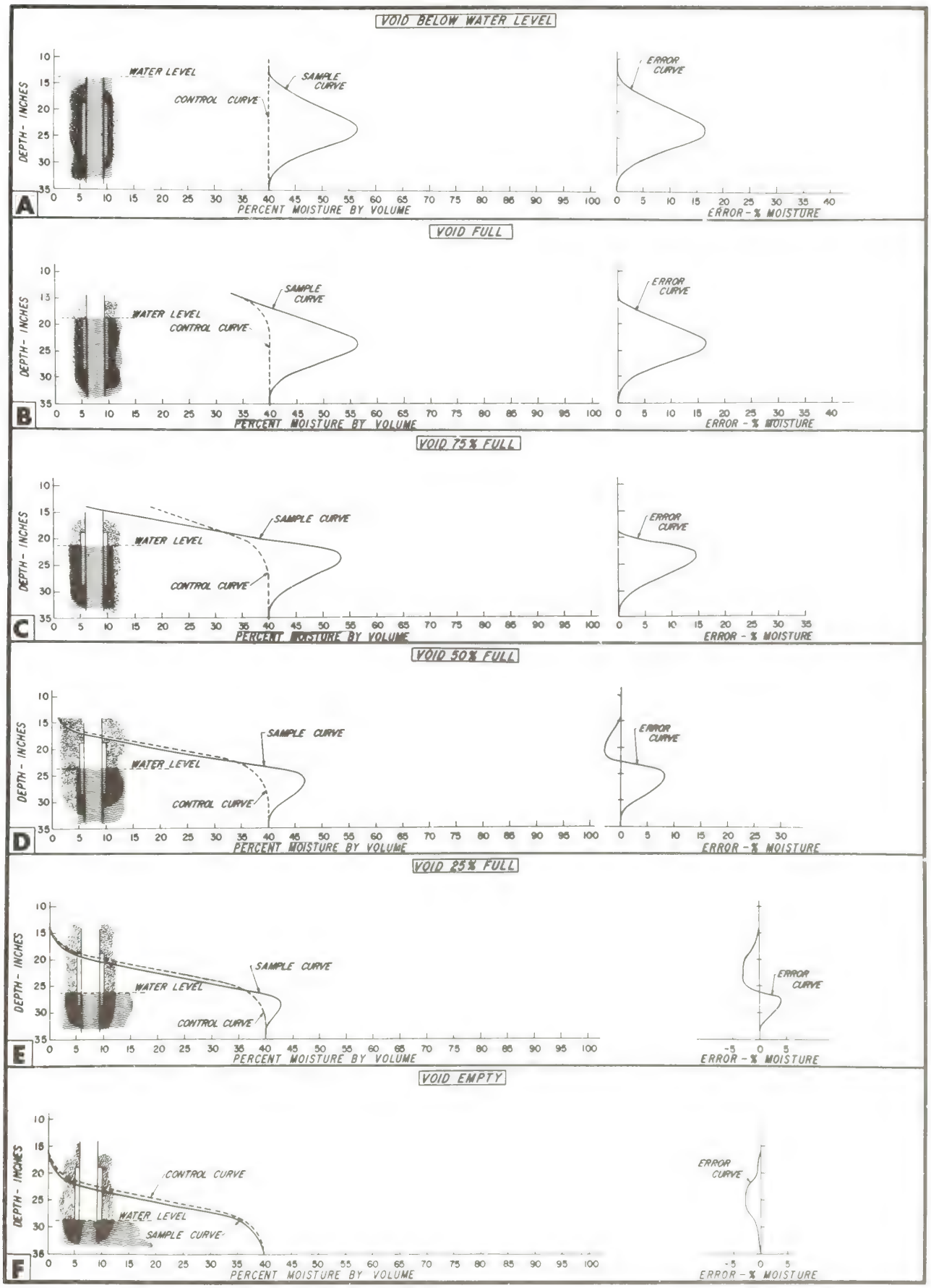

Figure 9. — The variation in neutron moisture measurements between control and sample tanks containing small voids is shown. Measurements were made using fine sand as the porous medium when the water level was changing with respect to the void.

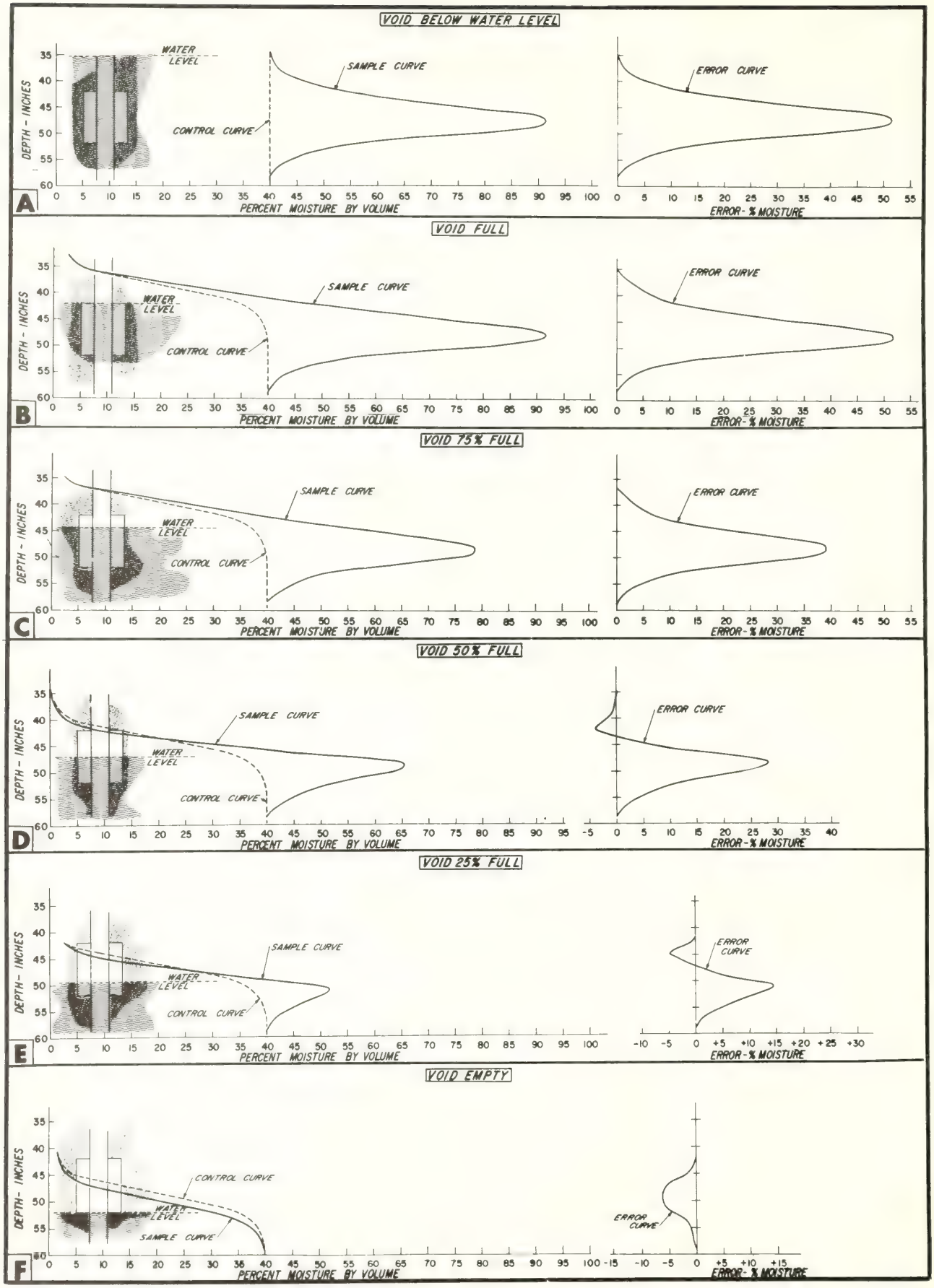

Figure 10. – The variation in neutron moisture measurements between control and sample tanks containing large voids is shown. Measurements were made using fine sand as the porous medium when the water level was changing with respect to the void.

Figures 9E and 9F show the continued increase in the amount of negative error as the water level is lowered within the small void. When the void was empty, the maximum measurement error was -3.0 percent by volume, and the total measurement error was -0.25 inch, from 16 inches below the surface to 35 inches below the surface.

Large Void--Fine Sand

Figures 10A through 10F show the same pattern of measurement-error change as the water level dropped within the large void. The maximum positive error was +52.2 percent moisture by volume with a maximum positive total error for the large void of +4.27 inches of water when the void was fully saturated. When the void was empty, the maximum negative error was -6.3 percent moisture by volume, and a maximum negative total error for the void of -0.50 inch of water.

It is interesting to note that when the measured medium contained less than 1 percent moisture, both curves are coincident and the voids caused no error (fig. 11).

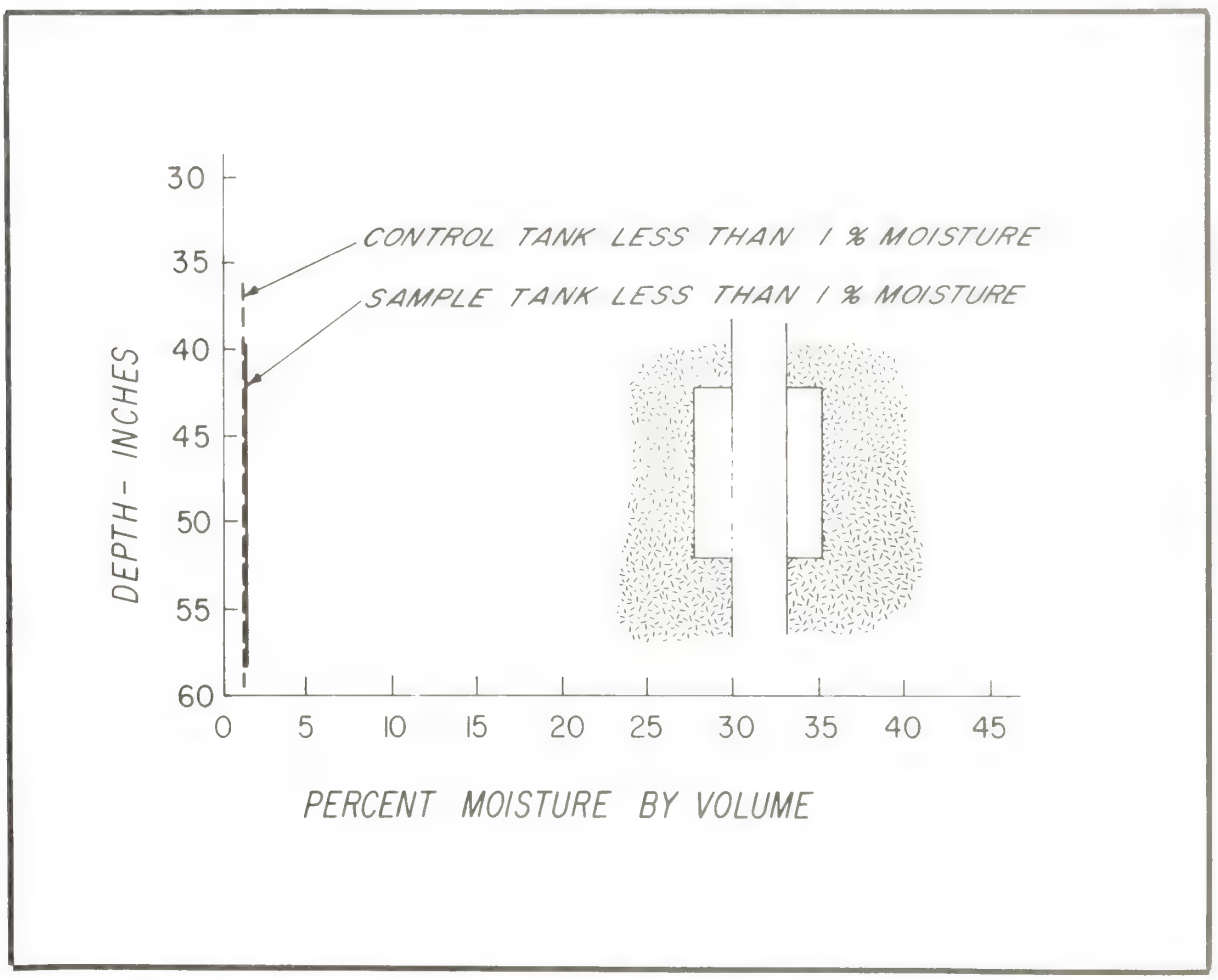

Figure 11. – When the measured medium contained less than 1 percent moisture, both moisture curves are coincident and the void causes no error.

DISCUSSION

Several conclusions can be drawn from figures 7 through 10. First, the presence of a void surrounding an access tube is most easily detected when the porous medium is saturated; this condition gives an error of the largest magnitude as shown in figures 7A, 8A, 9A, 10A, and table 2. The magnitude of the error at any level, and the magnitude of the total error, decrease as the water level falls with respect to the void. If the void is empty and the porous medium drained, the magnitude of the negative error is significantly less than the magnitude of the positive error.

The effect of the two densities of porous media is shown in figures 7A, 8A, 9A, 10A, and table 2. The material that has the highest bulk density gives the smallest value of positive measurement error and the lowest value of negative error. Figures 7A and 8A show that the total pore space of the coarse sand is 45 percent and figures 9A and 10A show that the total pore space of the fine sand is 40 percent. The increased amount of water in the coarse material caused a higher positive error. The smaller values of negative errors associated with the fine material were probably caused by reduced pore space.

Table 2. — Summary of maximum measurement errors and total errors for each void at each water level

Void size	Water level inches	Percent void saturation	Maximum measurement error %, moisture by volume[1]	Total error inches[2]
		COARSE SAND		
Small	Full	100	+17.5	+1.86
	18-3/4	100	+18.5	+1.79
	21-1/4	75	+19.2	+1.38
	23-3/4	50	-3.7 +10.3	+0.50
	26-1/4	25	-2.4 +4.5	+0.07
	28-3/4	0	-4.1	-0.35
Large	Full	100	+55.0	+5.64
	42	100	+55.0	+5.52
	44-1/2	75	-2.2 +55.0	+4.66
	47	50	-5.2 +41.3	+2.19
	49-1/2	25	-5.3 +12.6	+0.40
	52	0	-12.3	-0.99
		FINE SAND		
Small	Full	100	+16.5	+1.54
	18-3/4	100	+16.6	+1.42
	21-1/4	75	+14.8	+1.04
	23-3/4	50	-3.1 +8.4	-0.32
	26-1/4	25	-3.1 +4.2	-0.06
	28-3/4	0	-3.0	-0.25
Large	Full	100	+51.6	+4.17
	42	100	+52.2	+4.27
	44-1/2	75	+39.3	+3.19
	47	50	-3.9 +28.5	+1.67
	49-1/2	25	-4.8 +14.5	+0.56
	52	0	-6.3	+0.50

[1] *From error curve data — largest individual value.*

[2] *From error curve data — area under the curve with error expressed in inches of water instead of percent of volume.*

APPLICATION

The following example shows how the results of this laboratory study apply to field studies. Assume that soil moisture measurements are made at a certain depth within an access tube when the soil is saturated. If these measurements show a value of soil moisture which is greater than the maximum pore space of the soil, then a void adjacent to the tube should be suspected. Figure 12 illustrates such a hypothetical situation. The assumed maximum pore volume is 44 percent and the soil is assumed to be a coarse sand similar to that used in this study. This figure indicates that the soil moisture measurements, taken from late March to late June, are inaccurate because the measured soil moisture exceeds the maximum pore volume of the soil. If measurements are made at different depths in this tube during the time when the soil is saturated (in May for this example), the depth of the suspected void can be determined. Further measurements at 1-inch intervals may define a soil moisture curve similar to the solid line in figure 9A. A hypothetical field curve is shown as a solid line in figure 13 and illustrates the type of curve that might be encountered if there was a void partly filled with water. This field curve, which corresponds to the "control," is, of course, unknown; but a control curve may be drawn in after a study of the shape of the control curves in figures 7 through 10. An assumed control curve is shown as the dashed line in figure 13. The error curve is derived in the usual way from the horizontal displacement between the two curves and is shown at the right of figure 13; the total measurement error is the area ABCA. The 44 percent moisture ordinate is extended vertically until it intersects the hypothetical field curve at point D. Then a line is drawn horizontally from D to point E on the error curve. If the error curve is redrawn as the horizontal displacement between the control curve, the field curve, and the 44 percent ordinate, then this defines the error curve AEFA. Thus, soil moisture measurements may be made from a depth of 12 inches to a depth of 33 inches including a maximum estimated error of about +8.5 percent (at point E) instead of a maximum error of about 16 percent (at point B). The region of questionable data is shortened from the 12-inch level to about the 25-inch level instead of from the 12-inch level to the 33-inch level. The maximum measurement error is correspondingly reduced from +16 to +8.5 percent and the total error is reduced from 0.96 to 0.22 inch.

Figure 14 was derived from a plot of the maximum positive and maximum negative errors for both fine and coarse sand — a total of eight points taken from table 2. This graph can be used to estimate the volume of a suspected void provided that a field curve of neutron measurements can be made while the soil and void are saturated and provided that the saturated pore volume of the soil can be determined. In order to use figure 14, it is necessary to determine the maximum measurement error from field data. The field data are plotted, the saturated pore volume ordinate is superimposed, as in the left hand portion of figure 13, and the maximum measurement error is taken from this graph. Assume, for example, that the maximum measurement error for a completely saturated void in a coarse

sand was +36 percent moisture by volume. Then, figure 14 is entered at 36 percent and followed vertically to the error curve for the coarse material. Move horizontally from this intersection to the negative error curve for the coarse material; from this point, the estimated maximum negative error of -6.5 percent moisture by volume can be found on the abscissa. Also, by continuing left horizontally from the negative error curve to the ordinate, the estimated volume of 62.50 cubic inches for the void can be found. The estimated maximum negative error is of interest because this value may be difficult, if not impossible, to measure in the field when the void is empty. It should be kept in mind that figure 14 was derived from laboratory data obtained from symmetrical voids. It is not known whether figure 14 will provide accurate estimates of the volume of an asymmetric void.

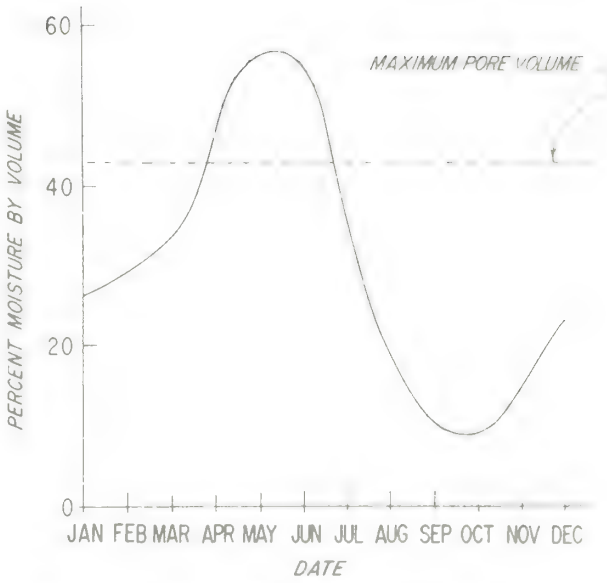

Figure 12. – Seasonal soil moisture for a given depth.

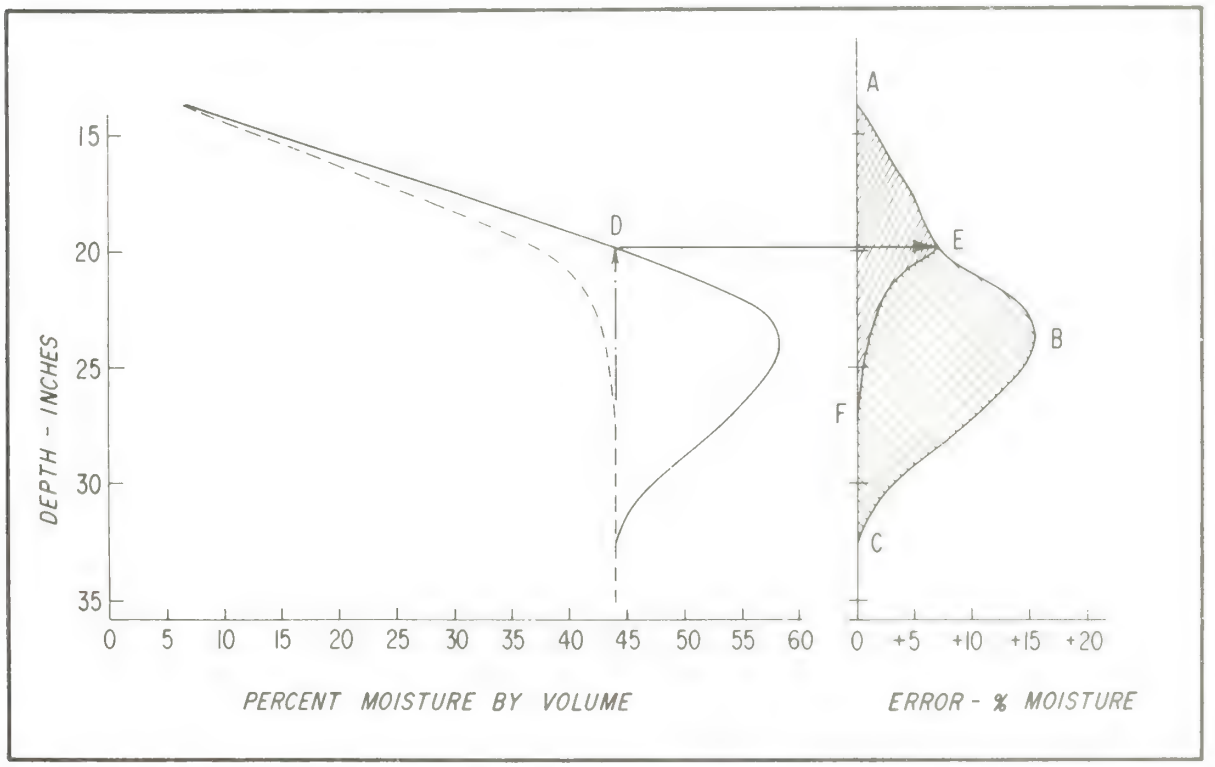

Figure 13. – Field data curve showing measurement error caused by a void partly filled with water.

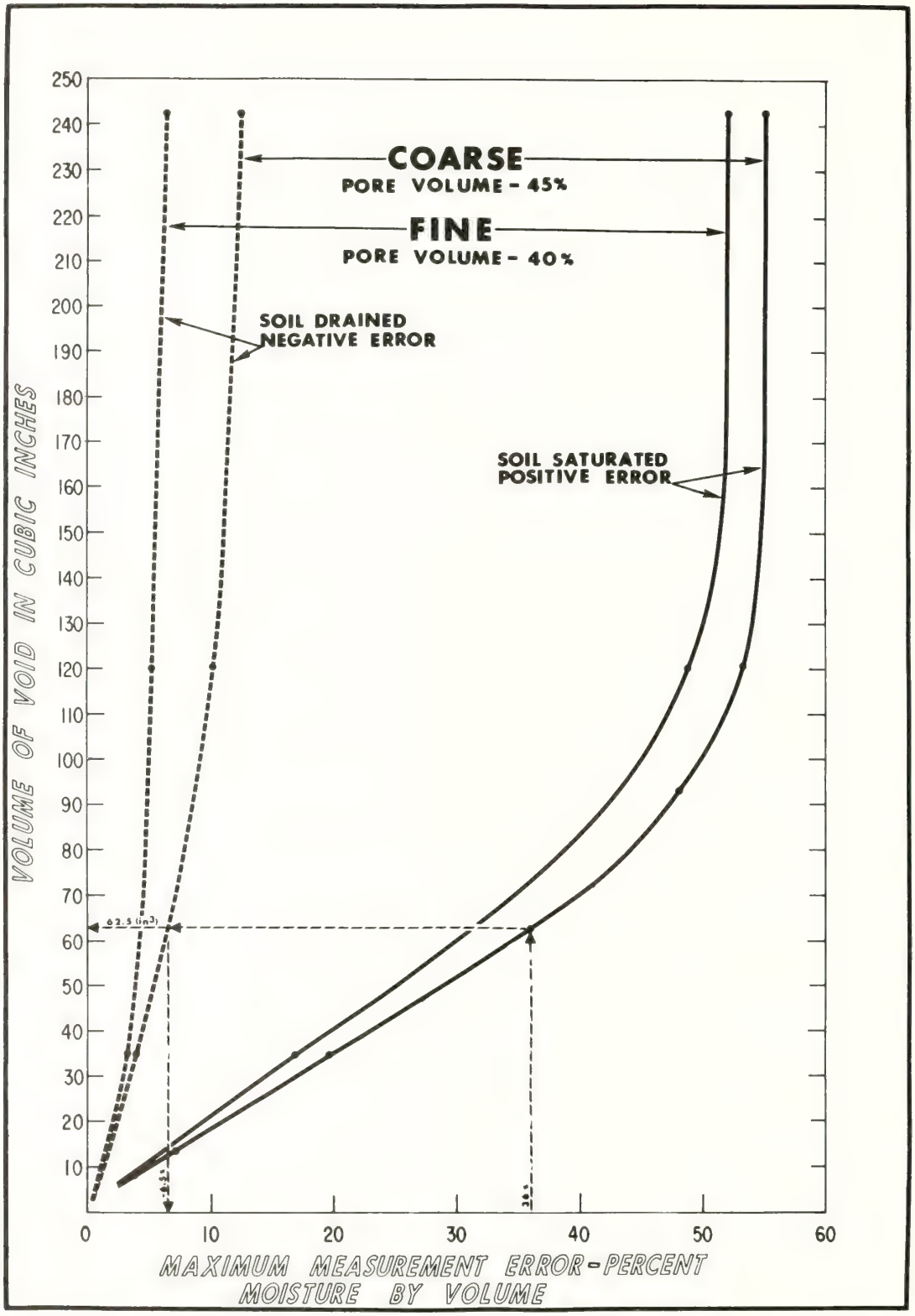

Figure 14. – Graph of volume of saturated void in cubic inches against the maximum measurement error in percent moisture by volume.

CONCLUSIONS

The figures and graphs of this paper are based on a laboratory study of the effect of air gaps and saturated voids on neutron moisture measurements. These results reflect the effect of symmetrical voids, each 10 inches long. Suggested procedures for estimating the amount and type of error (positive or negative) in field data may not yield accurate estimates for those voids which are greater than 3 inches in radius or shorter than 10 inches, or both. The Troxler equipment used in this laboratory study is nondirectional with respect to the axis of the void; therefore, the use of other neutron equipment which exhibits directional characteristics may yield significant differences when field studies are conducted on asymmetric voids.

The study described in this paper provides estimates of the maximum neutron measurement errors which may be expected for symmetric voids in a sand medium when the water is at different levels relative to the center of the void. Also, this study has shown that in the field the presence of a void can be determined most accurately when the soil is saturated. The magnitude of the positive measurement error will exceed that of the negative measurement error as long as any free water remains in the void.

Procedures which may be used to evaluate the magnitude of the measurement error from field data are outlined in this study. These procedures may be used to correct data for the effect of saturated voids surrounding the access tube, but they in no way reduce the importance of installing access tubes in such a way that there will be no voids next to the tube. Installation techniques together with descriptions of the equipment used have been reported elsewhere.

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RICHARDSON, BLAND Z., and BURROUGHS, EDWARD R., JR.

1972. Effects of air gaps and saturated voids on accuracy of neutron moisture measurements, USDA Forest Serv. Res. Pap. INT-120, 20 p., illus.

Presents study results showing effects of voids on accuracy of neutron soil moisture measurements. A maximum error of +55 percent moisture by volume was caused by a large void in coarse sand with the void saturated; with the void drained, the error was -12.3 percent moisture. Errors in fine sand were slightly less than in coarse sand; errors in small voids were about one-third the magnitude of errors in large voids. Graphs were developed to estimate size of voids adjacent to access tubes and to calculate probable magnitude of measurement errors due to these voids.

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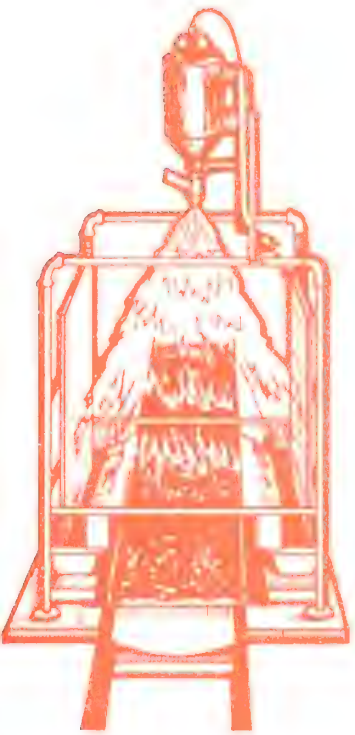
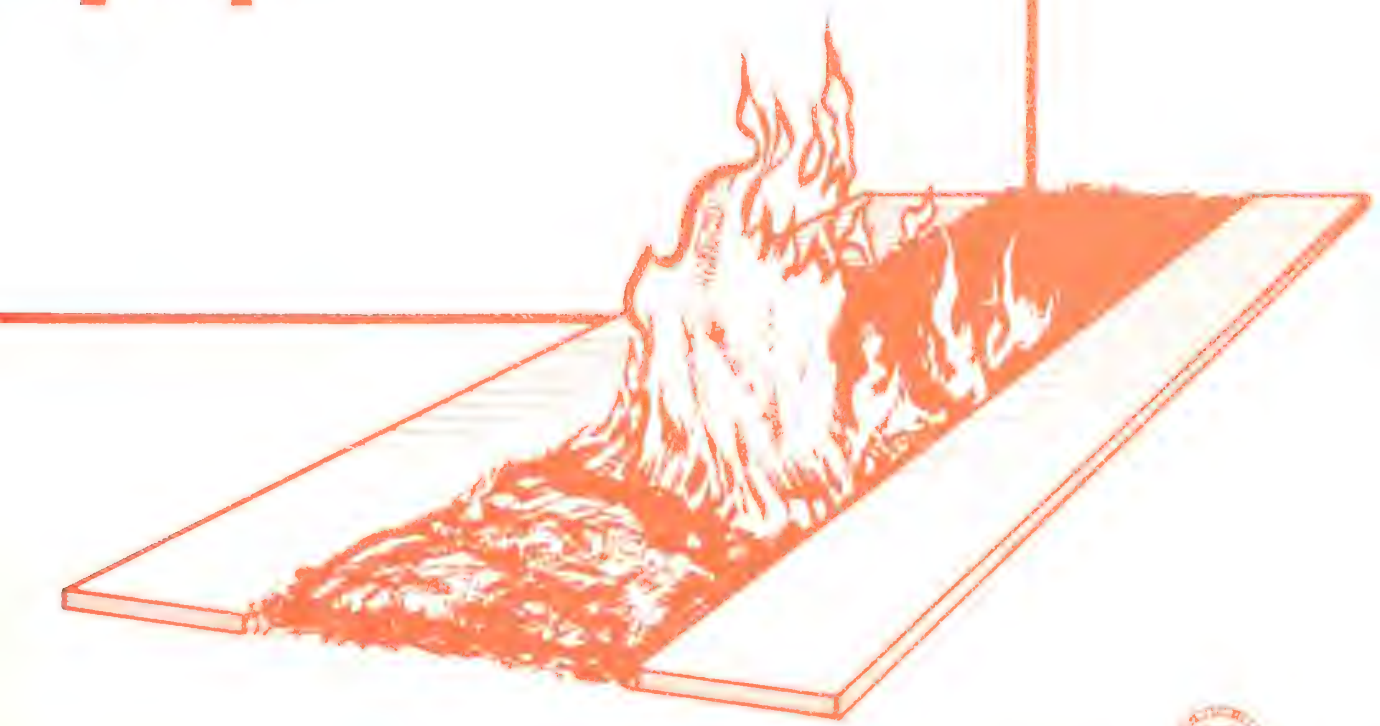
Effects Of Ammonium Sulfate And Ammonium Phosphate On Flammability

CHARLES W. GEORGE AND AYLMER D. BLAKELY





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ABSTRACT

Ponderosa pine needle and aspen excelsior fuel beds, chosen because they exhibit different chemical fuel characteristics, were treated with various amounts of ammonium sulfate and ammonium phosphate and burned in a wind tunnel under controlled environmental conditions. The rate of fire spread, rate of weight loss (equivalent energy release rate), and the residue were measured to quantify the retardants' effects on flammability.

An increase in the amount of either fire retardant chemical caused a reduction in rate of fire spread and rate of weight loss while increasing the amount of residue. However, at all treatment levels, ammonium phosphate was more effective than ammonium sulfate. These two chemicals exhibit their primary difference in their effect on glowing combustion. The rate of weight loss and especially the residue are parameters that quantify glowing combustion.

Ammonium phosphate is much more effective in decreasing the rate of weight loss and increasing the residue than is ammonium sulfate, which has little effect on the residue. The superior effectiveness of ammonium phosphate is probably due to the difference in thermal behavior of the two fire retardants; total decomposition of ammonium sulfate occurs prior to 450° C., about 250° C. sooner than ammonium phosphate. Temperatures at the surface of the fuel bed probably are within the range of these total decomposition temperatures. Although ammonium sulfate is effective in retarding flaming combustion, the majority of the chemical may decompose prior to the glowing phase and thus not be available to alter reactions taking place during glowing combustion.

The study provides general relationships which can serve as standards for comparing the effects of other basic chemicals or forest fire retardant additives.

INTRODUCTION

The Problem

More than 80 million gallons of fire retardant have been used in the control of forest and rangeland fires by fire control agencies throughout the United States in the last 10 years. These fire retardants are specially formulated and usually contain: an active retardant chemical; coloring agent; corrosion inhibitor; thickening agent; and spoilage inhibitor, when necessary.

The most commonly used active retardant chemicals are ammonium sulfate $(NH_4)_2SO_4$ and ammonium phosphate $(NH_4)_2HPO_4$. These chemicals, when applied to cellulosic fuels, alter the combustion process to produce less flammable products while increasing the amount of nonflammable products. The most efficient use of these chemicals can only be made after thorough quantification of their effects on flammability.

Flammability has been defined as the interaction of ignitibility, sustainability, and combustibility (Anderson 1970). Ignitibility is the ease with which a fuel will ignite. Under given conditions, the most ignitible fuel will ignite with the least energy input. Sustainability is a measure of how well the fuel will continue to burn with or without the heat source after ignition. Combustibility is a measure of the rapidity with which energy is released from the fuel following ignition.

Fire retardant chemicals are often applied to reduce the overall flammability of fuels. In other instances these chemicals are used specifically to reduce the sustainability or combustibility. It is often thought that ignitibility is decreased by treating fuel with retardant chemicals such as ammonium sulfate and ammonium phosphate; however, recent empirical data indicate the reverse--i.e., less energy is necessary for ignition of treated fuel.[1] This fact is substantiated by more sophisticated thermal analysis data which indicate that treated cellulose undergoes pyrolysis and combustion at lower temperatures and with less energy inputs than does untreated cellulose (George and Susott 1971). (Pyrolysis is the thermal degradation of a material.)

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[1]Unpublished experimental data on file at the Northern Forest Fire Laboratory, USDA Forest Service, Missoula, Montana.

A study of the effects that ammonium sulfate and ammonium phosphate have on flammability must include quantification of several appropriate parameters. Many researchers have used rate of fire spread to assist in the evaluation of fire retardants (Hardy, Rothermel, and Davis 1962; Rothermel and Hardy 1965; Johansen 1967; Eickner and Schaffer 1967). The rate of spread is a measure of sustainability, or the ability of a fire to propagate itself. The combustibility, or rate at which energy is released from the fire, can be measured by monitoring the weight loss rate that occurs during the fire (Rothermel and Hardy 1965; Rothermel and Anderson 1966). Only recently has it been pointed out that retardant chemicals applied to open fuel bed fires may have similar effects on the rate of spread but different effects on the rate of energy release (George and Blakely 1970). Because fire retardants are used to reduce fire spread and combustion rate, it is necessary for both parameters to be quantified.

Although ignitibility and sustainability may be encompassed in rate of spread measurements, and combustibility in energy-release rate measurements, they do not entirely describe a fire retardant's effect on flammability. Combustion can be divided into two phases: flaming (associated mainly with the fire front); and glowing (associated with residual burning)--different rates of energy release apply for each of these. The retardant chemical, due to inherent decomposition characteristics, may only be available at given temperatures or for a given time during the fire, (George and Susott 1971) thus causing different effects on the flaming and glowing processes. The extent of combustion, both flaming and glowing, can be determined by measuring the amount of residue.

The quantification of the effects that fire retardants have on rate of spread, energy release rates, and residue should provide a basis for determining the chemical's overall effect on flammability.

Objectives

The major objective of this study was to determine the effects of ammonium sulfate and ammonium phosphate on the flammability of cellulosic fuels. The overall effects on flammability can be characterized by quantification of these effects on the following parameters:

1. Rate of spread (R_s)
2. Rate of weight loss (R_w)
3. Residue (R)

Standard curves were developed in this study for each parameter as a function of the amount of retardant chemical applied to the fuel.

The study was designed to provide general information which can be used to evaluate formulated ammonium sulfate and ammonium phosphate fire retardants. The curves will be used to evaluate the relative importance of additives, or impurities, and to determine whether they enhance or reduce the active chemicals' effectiveness. This information will be useful to potential suppliers for the formulation of more efficient fire retardants.

Also, this study will provide information which may eventually be used in the development of operational guidelines. The guidelines could assist fire control personnel in selecting the most efficient retardant chemical for a given job and help determine how much chemical is required for the specific situation.

Table 1.--*Comparison of chemical characteristics of ponderosa pine needles and aspen excelsior*

Item	Aspen excelsior	Ponderosa pine needles
Cellulose (percent dry weight)	42.0	18.0
Ash content (percent dry weight)	0.36	3.87
Silica-free ash (percent dry weight)	0.36	1.55
Ether extractives (percent dry weight)	<1.0	9.73
Heat content (B.t.u./lb.)	8,485	8,753

Ponderosa pine needles for fuel beds were collected and cleaned during the year prior to the tests. The needles were stored indoors until an equilibrium moisture content was reached, and aspen excelsior which had been cut to specifications was given similar treatment. Following this ambient indoor conditioning, moisture contents were between 5 and 8.5 percent (percent of ovendry weight) for both types of fuel.

Fuel beds, fuel bed configuration, and a method of preparation similar to that used by Rothermel and Hardy (1965) was adopted for use in the study. A lighter fuel loading was necessary for aspen excelsior because of its higher surface area-to-volume ratio. Characteristics of the fuel bed are shown in table 2.

Method of Chemical Application

A method of application was developed and used to distribute the retardant solution uniformly over the surface of the fuel bed at a constant depth of penetration. This was accomplished by applying a constant volume of solution and varying only the concentration or amount of the chemical in solution. The solution was contained in a pressurized supply tank that had a calibrated flow. The calibration was established by

Table 2.--*Fuel bed characteristics*

Fuel bed (Inches)	Average equilibrium moisture content	Loading at EMC		Fuel surface-to-volume ratio	Fuel bed void volume-to-surface-to-area ratio
	Percent	*Lb./bed*	*Lb./ft.*^{2}	σ *ft.*^{2}*/ft.*^{3}	λ *ft.*^{3} */ft.*^{2}
Aspen excelsior					
3 by 18 by 36[1]	7.0	1.5	0.33	1,848	9.36 by 10^{-3}
3 by 18 by 96	7.0	4.0	.33	1,848	9.36 by 10^{-3}
Ponderosa pine needles					
3 by 18 by 36[1]	7.5	2.25	.50	1,741	8.46 by 10^{-3}
3 by 18 by 96	7.5	6.0	.50	1,741	8.46 by 10^{-3}

[1] Igniter tray.

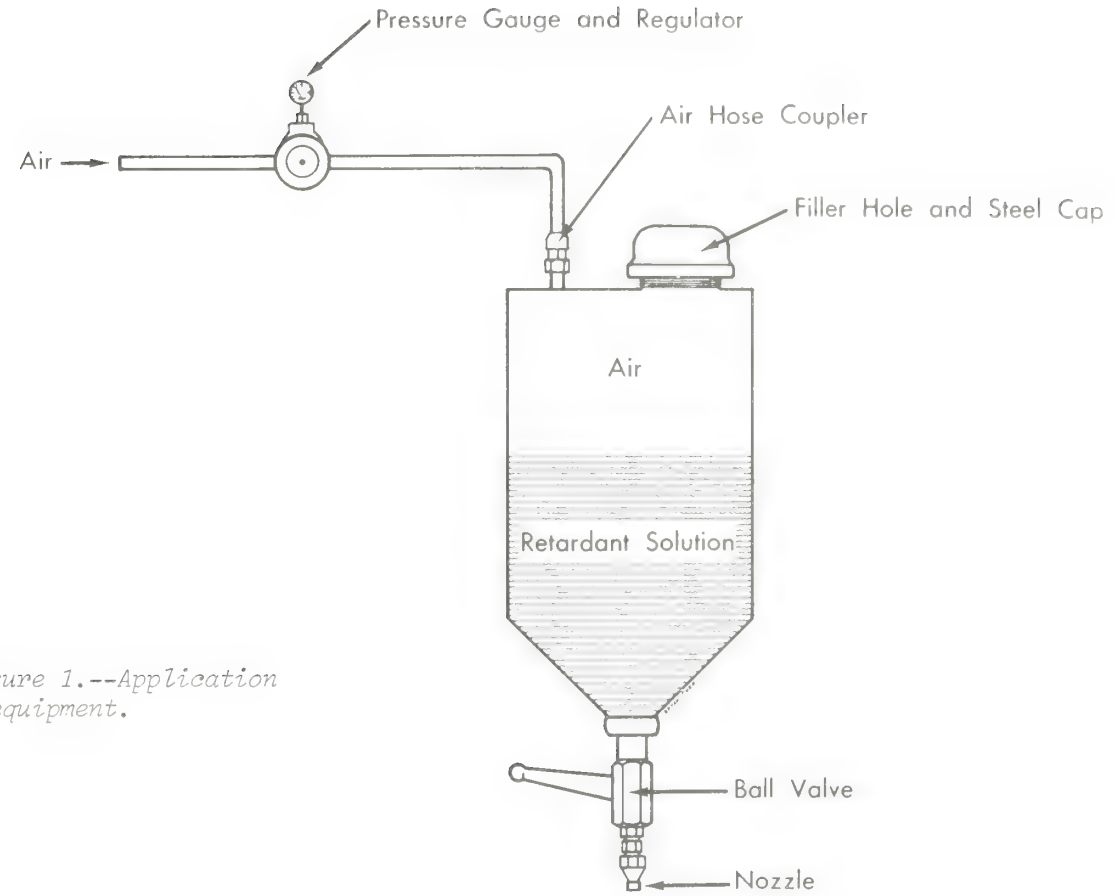


Figure 1.--Application equipment.

determining the volume rate through the nozzle at a given pressure while measuring the lateral spray pattern. A nozzle diameter, height, and tank pressure were selected that would provide a uniform lateral pattern over the fuel bed width. The fuel beds were then pushed under the nozzle at a constant predetermined speed to apply the desired amount of solution. The application equipment and spray system in operation are shown in figures 1 and 2.

The fuel beds were weighed prior to and following application of the retardant solution. The amount of solution per square foot of fuel bed and the percent of solution as a function of dry fuel weight were calculated.

Conditioning of Fuel and Environmental Conditions

Following application of the retardant solution, the fuel beds were allowed to reach an equilibrium moisture content in the combustion chamber under controlled environmental conditions. The combustion chamber air temperature was held at 90° ±2° F. and the relative humidity at 20 ±2 percent. A new equilibrium moisture content of between 5.0 and 6.5 percent was reached. Equilibrium was determined by periodic weight checks of the fuel bed, and the moisture content was determined by using the xylene distillation method.

All burning tests were made in a large wind tunnel at an air velocity of 5 m.p.h. Fuel bed conditioning and the burning tests were conducted under similar temperature and relative humidity conditions. These conditions are equivalent to a Fine Fuel Spread Index of 36 (USDA Forest Service 1964).

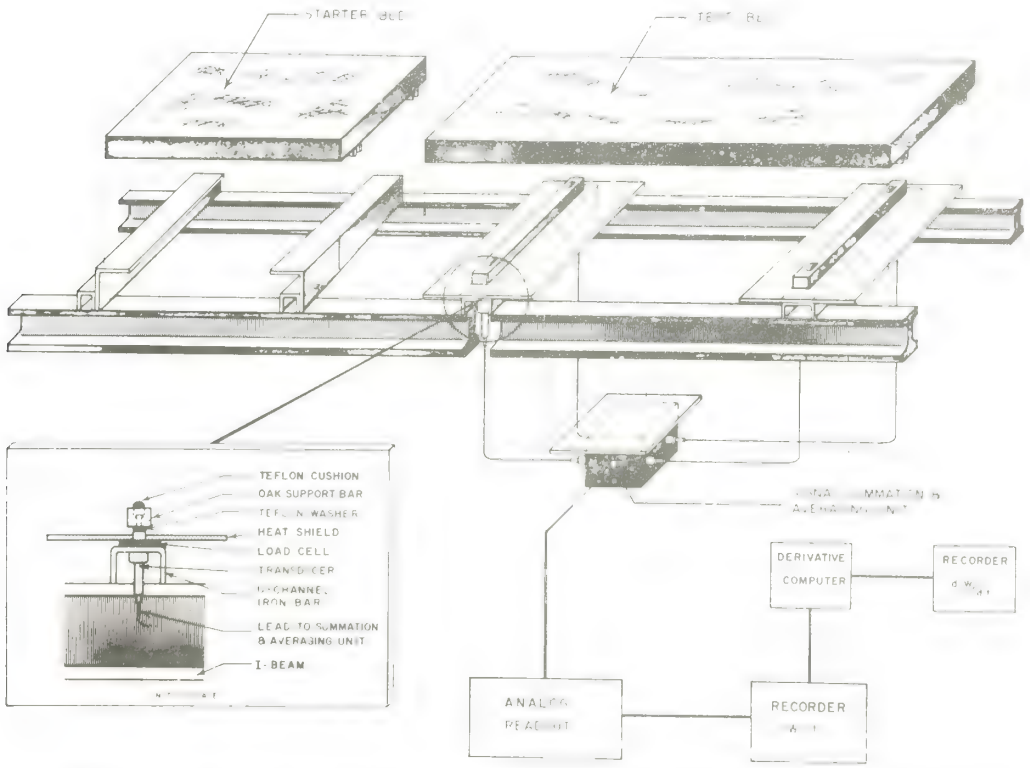
Figure 2.--Spray system in operation.

BURNING TEST

Burning Procedures

Treated and conditioned fuel beds were removed from the combustion chamber and placed on the weighing system in the wind tunnel. The weighing system, described by George and Blakely (1970), was a multiple point system capable of monitoring a weight loss from 0 to 6 pounds, depending on the fuel type and loading; sensitivity of the system was about ±0.25 percent, or ±0.001 pound. The weighing system utilized transducer-type elements and load cells manufactured by the Statham Instrument Company. The signal from these transducers was summed and averaged to produce a single direct measurable output and then recorded.

Aprons were placed on all sides of the treated fuel beds and the starter beds to produce uniform airflow over the fuel surfaces. A small tray of ethanol (approximately 25 ml.) at the bottom edge of the igniter tray gave uniform ignition at the leading edge. Just prior to test time, a remote controlled electric spark was produced to ignite the ethanol. The positioning of the beds and a schematic of the weighing system are shown in figure 3. The positioning of side aprons and fuel beds during burning is shown in figure 4.



positioning of starter and treated fuel beds.

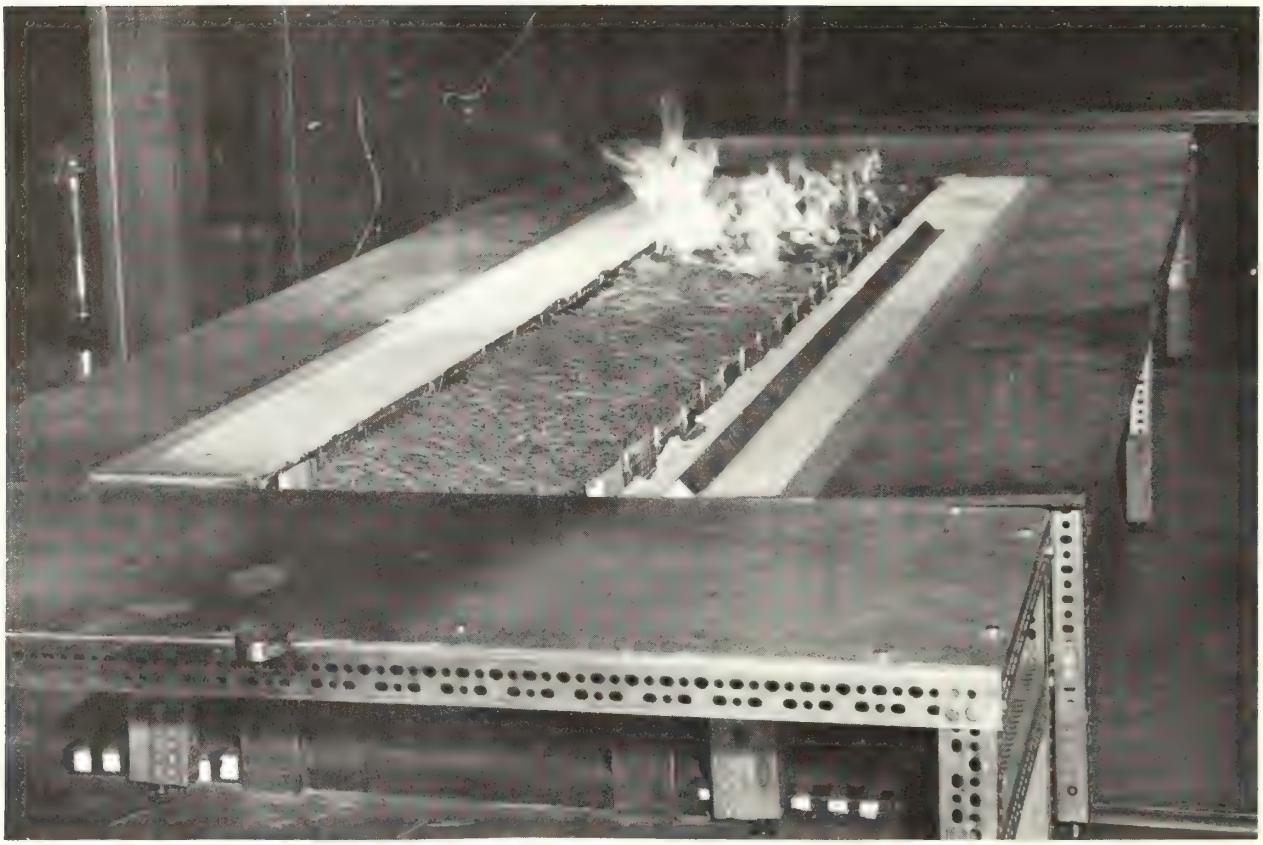


Figure 4.--Positioning of fuel beds and side aprons during test fire.

Measurements

Rate of Spread

The rate at which fire spread through the fuel was measured visually. An aluminum strip with marks at each half-foot interval lay alongside the treated bed. An observer, with a remote switch, activated an event marker which was attached to a recorder being used to record weight loss. The time required for the fire front to cover each half-foot interval was measured and the average steady-state rate of spread between the 3- and 7-foot mark calculated.

Weight Loss Rate

The weight of the treated fuel bed was monitored during the fire on a recorder which had previously been calibrated for a full scale deflection of 4.4 pounds (2,000 grams). The weight loss at the 3- and 7-foot intervals was determined. The time between these intervals was computed from the rate-of-spread event marks and then the steady-state rate of weight loss was calculated.

Residue

The fuel was allowed to burn until glowing combustion was completed; then the fuel bed was weighed and the residue determined.

Figure 5 shows a burning test in progress and the equipment being used for taking the required measurements.

Figure 1.--Instrumentation set-up used during test flights.

RESULTS

A total of 133 treated and untreated fuel beds were burned during the study. Of these, 73 were composed of ponderosa pine needles and the remaining were aspen excelsior. The treated beds received applications of $(NH_4)_2SO_4$ or $(NH_4)_2HPO_4$. Data for the untreated fuel beds are given in table 4 of the appendix. A summary of the test data for $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ treated ponderosa pine needle fuel beds is presented in tables 5 and 6 of the appendix. A summary of the test data for treated aspen excelsior fuel beds is given in tables 7 and 8 of the appendix.

The relationship between the amount of chemical applied per square foot of fuel bed and the rate of fire spread through the pine needle and excelsior fuel beds is shown in figures 6, 7, 8, and 9. The rate of weight loss and equivalent energy release rate (assuming the energy released is equal to heat content of the fuel times the weight loss rate) as a function of the amount of chemical for the two types of fuel beds are shown in figures 10, 11, and 12. The percent increase in residue over the average residue for untreated was calculated for each fire. This percent increase in residue as related to the amount of chemical applied is shown in figures 13 and 14.

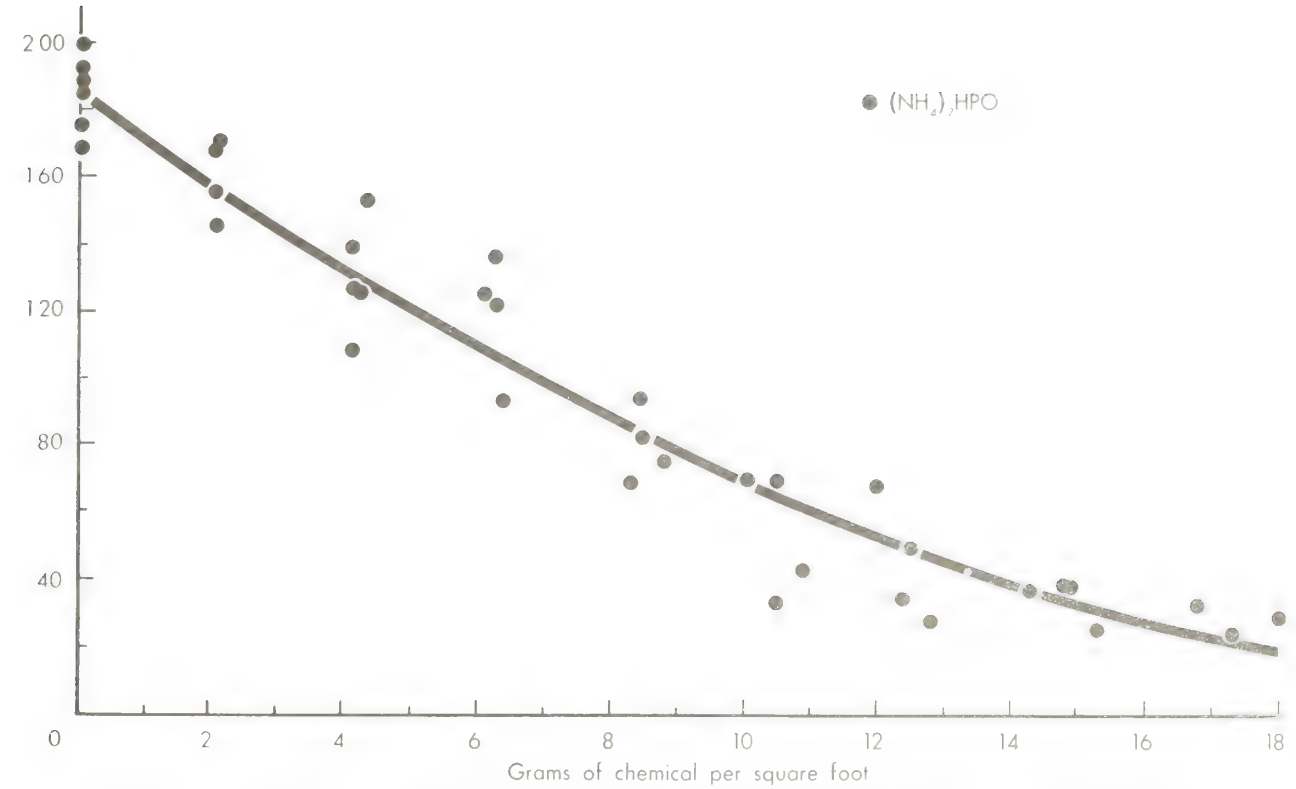


Figure 6.--Effect of $(NH_4)_2HPO_4$ on the rate of spread in pine needle fuel.

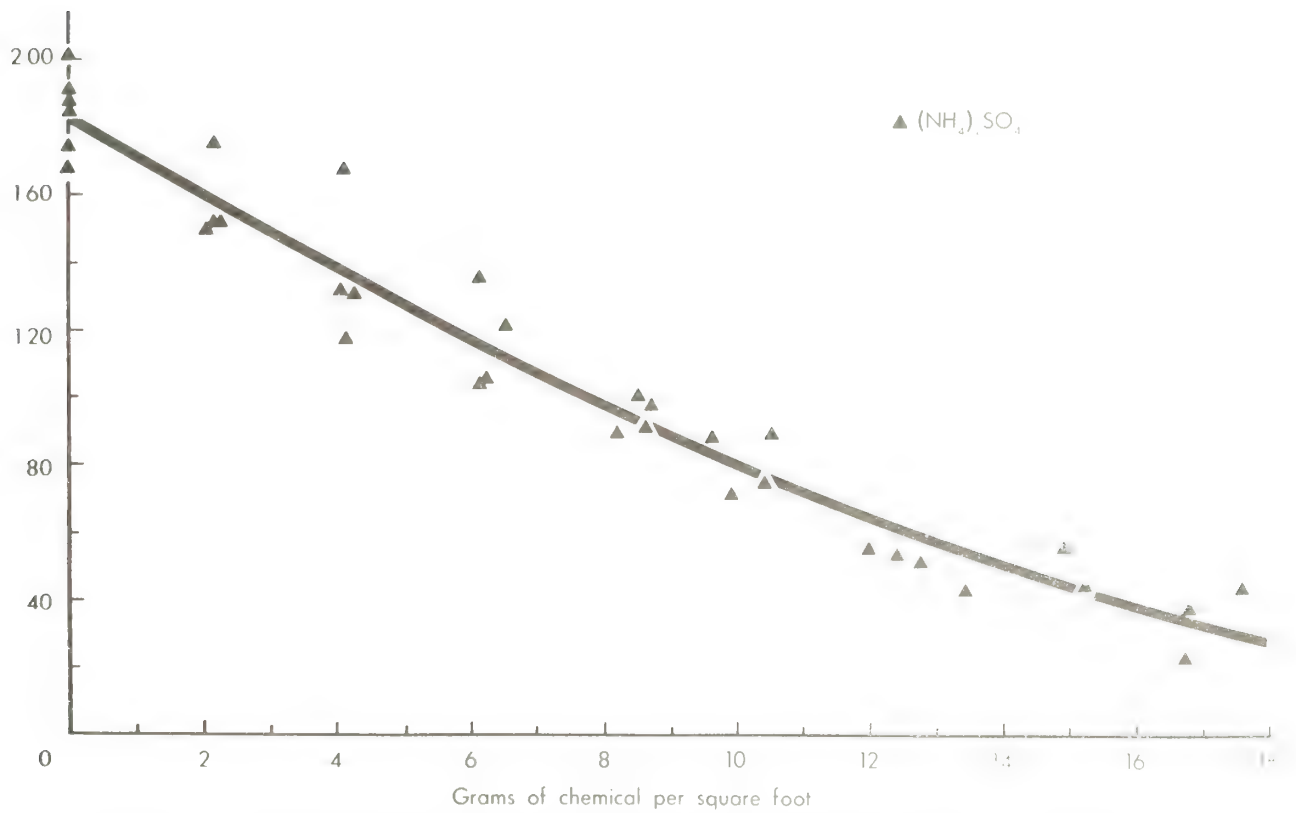
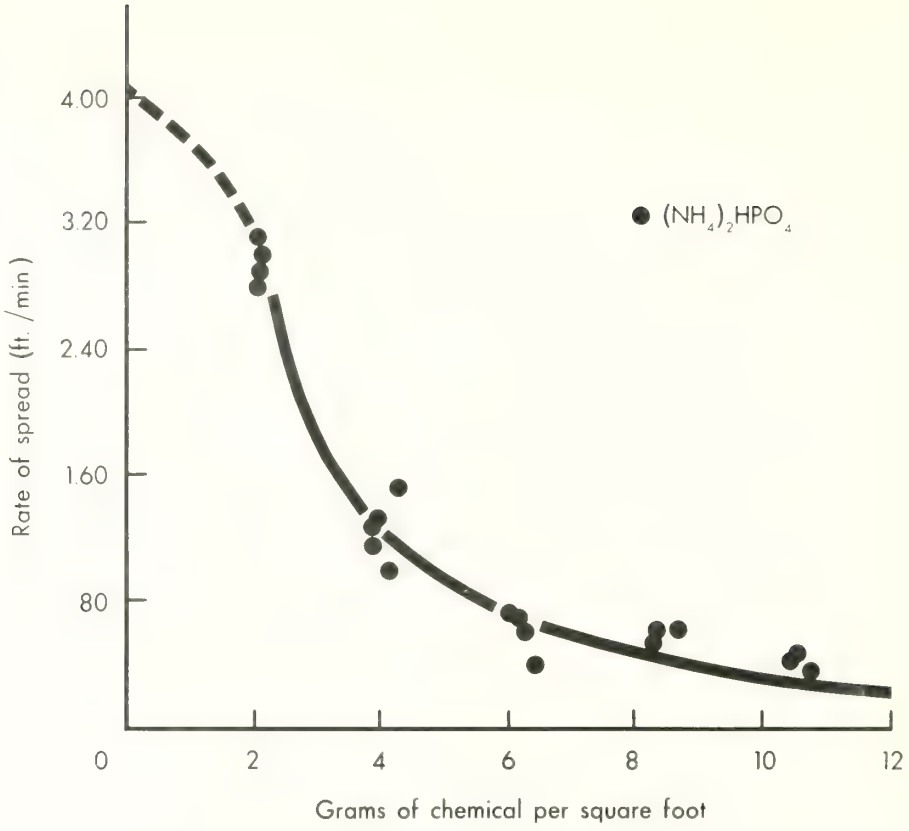


Figure 7.--Effect of $(NH_4)_2SO_4$ on the rate of spread in pine needle fuel.

Figure 8.--Effect of $(NH_4)_2HPO_4$ on the rate of spread in excelsior fuel.



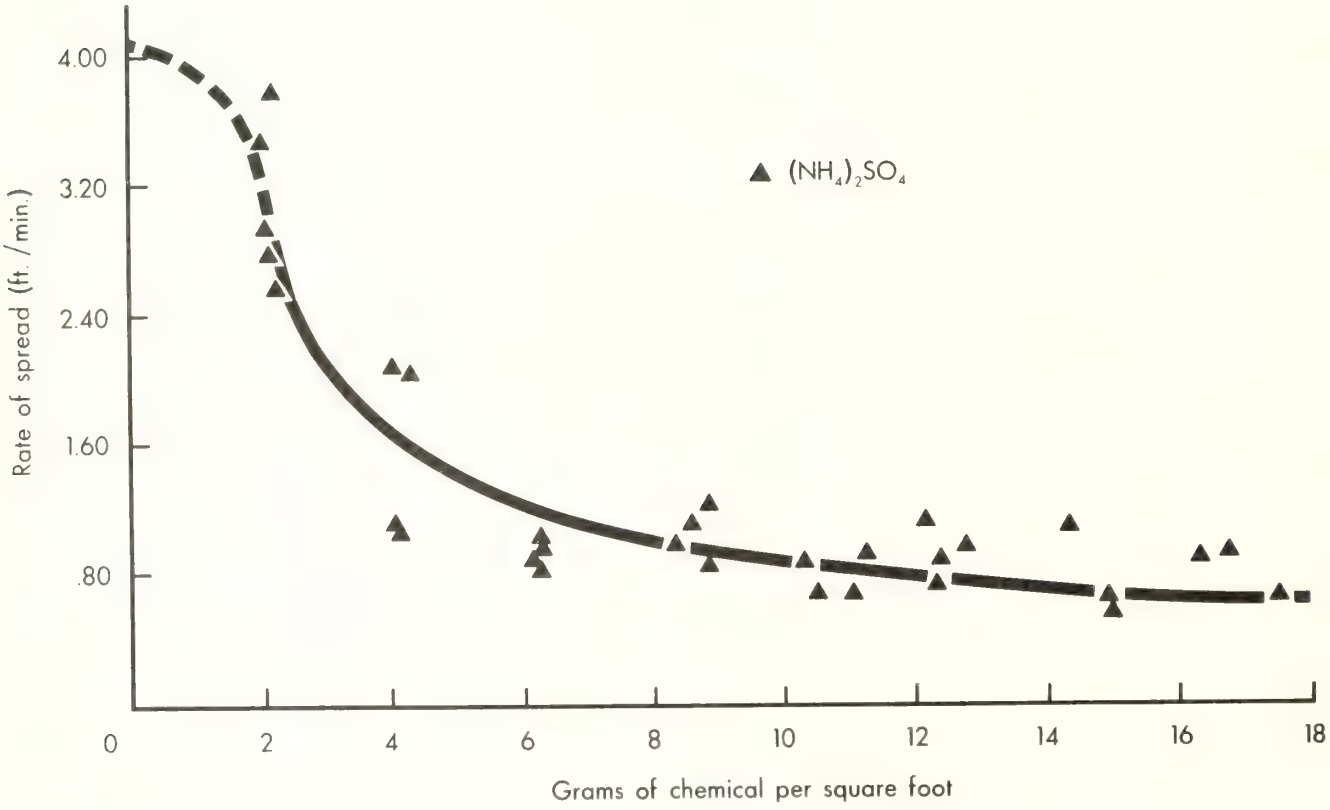


Figure 9.--Effect of $(NH_4)_2SO_4$ on the rate of spread in excelsior fuel.

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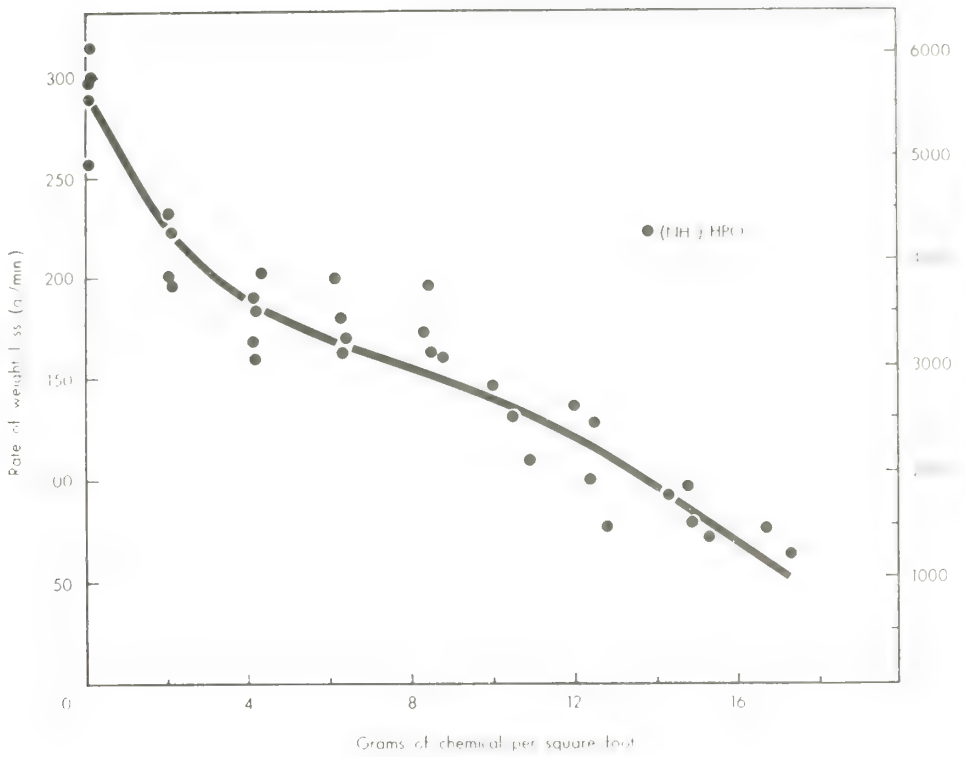
elease rate in pine



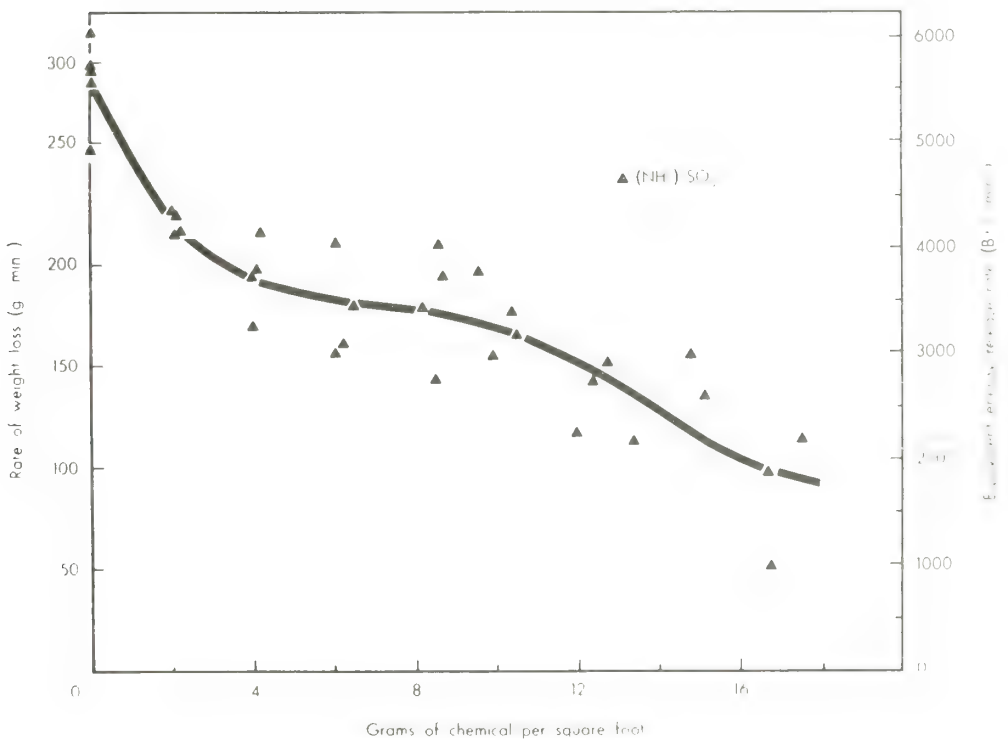


Figure 11.--Effect of $(NH_4)_2SO_4$ on the rate of weight loss or equivalent energy release rate in pine needle fuel.

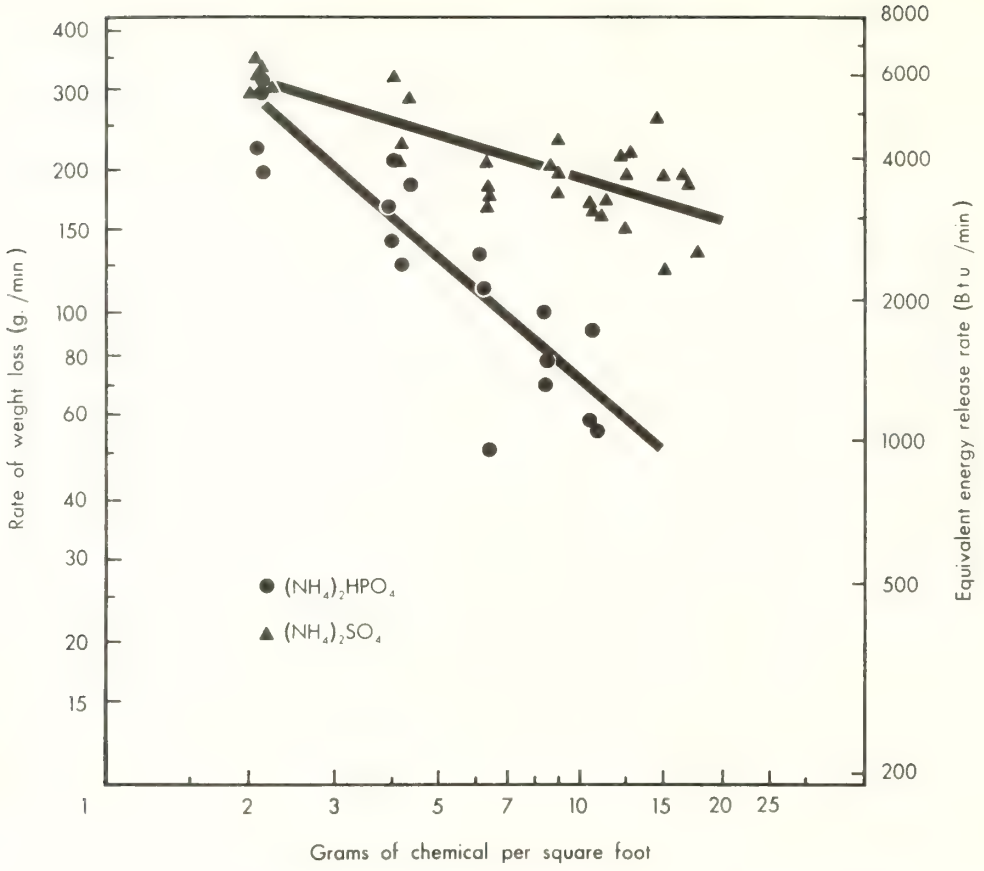


Figure 12.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on the rate of weight loss or equivalent energy release rate in excelsior fuel.

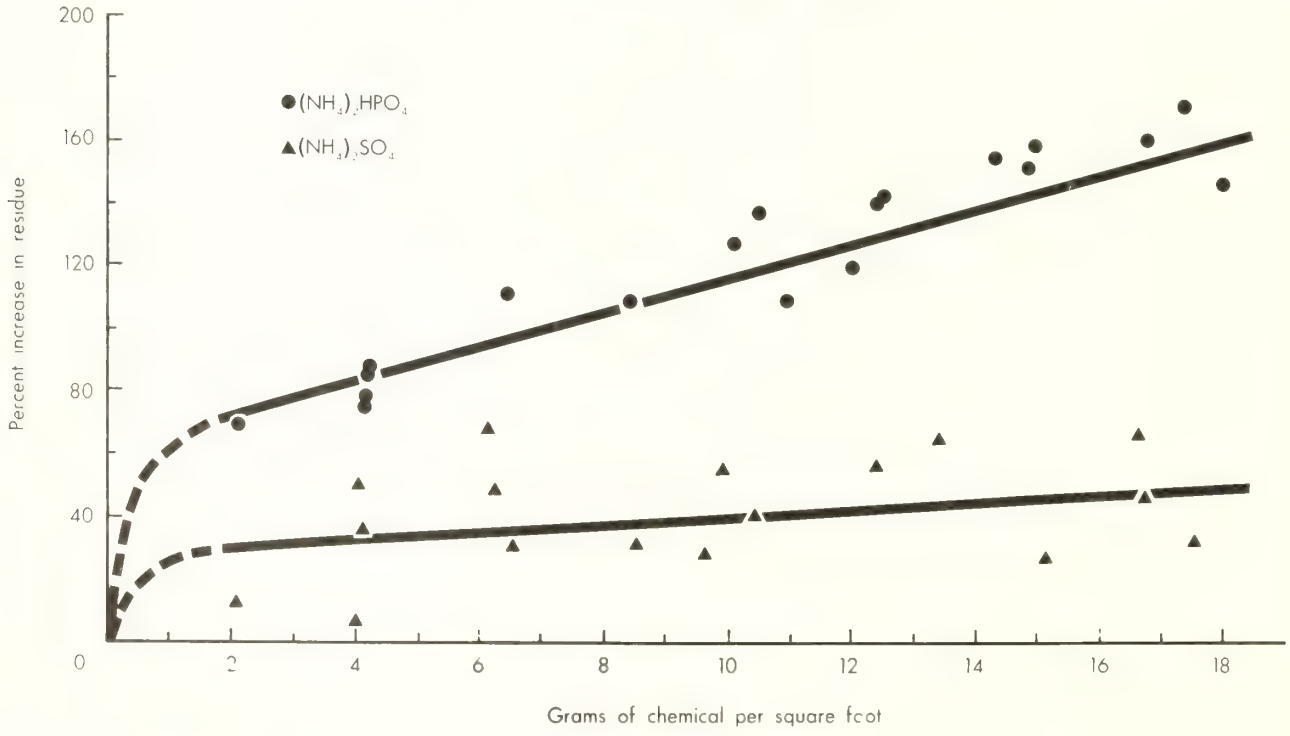


Figure 13.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on the residue in pine needle fuel.

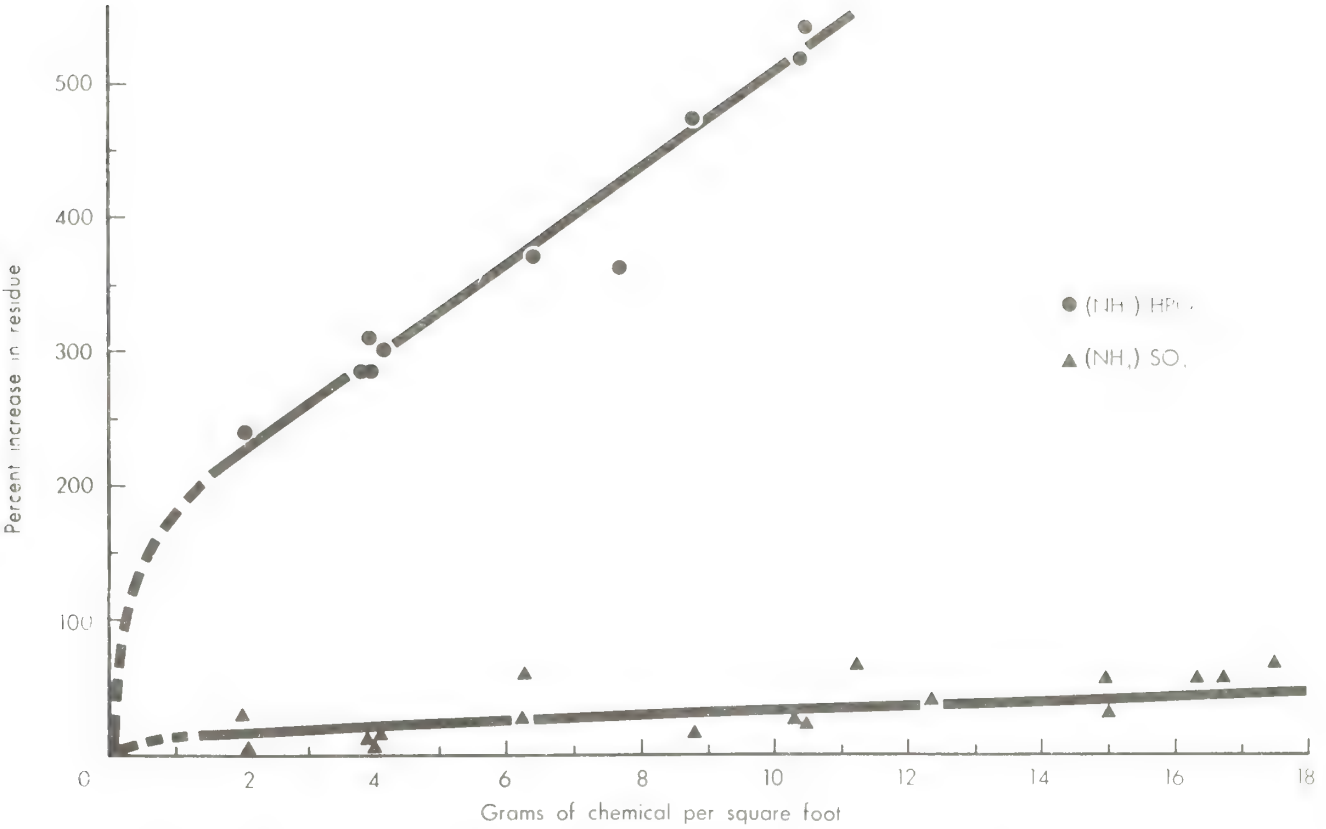


Figure 14.--Effect of $(NH_4)_2HPO_4$ vs. $(NH_4)_2SO_4$ on the residue in ponderosa pine needle fuel.

Regression equations were determined for each relationship. The data for both chemical treatments of the same fuel type were then pooled and an analysis of covariance completed. A measure of how well each regression equation fits the sample data is shown by the coefficient of determination, r^2. The r^2 for each relationship and the r^2 and the F (variance ratio) for the pooled data are given in table 3.

The statistical data indicate that for all parameters measured and for both ponderosa pine needle and aspen excelsior fuel, ammonium phosphate and ammonium sulfate have significantly different effects. The rate of spread in pine needles as a function of the amount of chemical, for both treatments, was the only dependent variable that was not significantly different at the 99 percent level (see table 3).

The regression equations in table 3 (also appendix tables 4 through 8) show that ammonium phosphate reduces the rate of fire spread and rate of weight loss (or equivalent energy release rate) to a greater degree than ammonium sulfate in both the excelsior and pine needle fuel beds. Ammonium phosphate also caused a greater increase in residue, thus decreasing the total energy released.

Ammonium phosphate is more effective than ammonium sulfate in reducing all parameters measured in the study; the largest difference occurs in the greater ability of ammonium phosphate to decrease the rate of weight loss or energy release rate and increase the amount of char or residue formed. Residue in pine needle fuel beds treated with ammonium phosphate showed an 80 to 160 percent increase over residue formed in untreated beds. Ammonium sulfate used under the same conditions did not increase the amount of residue beyond 50 percent. Excelsior fuel beds treated with ammonium phosphate showed an increase in residue of 200 to 500 percent, depending on the treatment level; ammonium sulfate increased the residue only about 50 percent. Figures 15 and 16 show the effects of ammonium sulfate and ammonium phosphate on the residue of combustion occurring in ponderosa pine needle and aspen excelsior fuel beds.

Parameter	Treatment	n	Equation	r^2	F(variance ratio)[1/]	Significance percent[2/]
Ponderosa pine needles						
Rate of spread (R_S)						
	$(NH_4)_2HPO_4$ (DAP	44	$y = 1.83 - 0.143(x) + 0.00289(x^2)$	.95		
	$(NH_4)_2SO_4$ (AS)	41	$y = 1.81 - 0.119(x) + 0.00184(x^2)$	.96		
	Pooled	85	$y = 1.82 - 0.131(x) + 0.00234(x^2)$	.95	3.15 (f = 3, 7-)	95
Rate of weight loss (R_W)						
	$(NH_4)_2HPO_4$ (DAP)	43	$y = 292 - 43.7(x) + 5.98(x^2) - 0.399(x^3) + 0.00883(x^4)$	.94		
	$(NH_4)_2SO_4$ (AS)	40	$y = 294 - 48.7(x) + 8.05(x^2) - 0.583(x^3) + 0.0140(x^4)$	.91		
	Pooled	83	$y = 292 - 43.3(x) + 6.05(x^2) - 0.394(x^3) + 0.00848(x^4)$	.91	4.13 (f = 5, 73)	99
Residue (R)						
	$(NH_4)_2HPO_4$ (DAP)	19	$y = 60.4 + 6.06(x)$	.91		
	$(NH_4)_2SO_4$ (AS)	17	$y = 29.5 + 1.18(x)$	.11		
	Pooled	36	$y = 40.0 + 4.43(x)$	.20	165.4 (f = 2, 32)	99
Aspen excelsior fuel beds						
Rate of spread (R_S)						
	$(NH_4)_2HPO_4$ (DAP)	19	$y = -0.332 + 6.67(x^{-1})$	.97		
	$(NH_4)_2SO_4$ (AS)	31	$y = 0.330 + 5.50(x^{-1})$	.87		
	Pooled	50	$y = 0.147 + 5.68(x^{-1})$	.86	15.0 (f = 2, 46)	99
Rate of weight loss (R_W)						
	$(NH_4)_2HPO_4$ (DAP)	19	$\ln y = 6.19 - 0.841 \ln x$	.79		
	$(NH_4)_2SO_4$ (AS)	31	$\ln y = 5.95 - 0.295 \ln x$	.60		
	Pooled	50	$\ln y = 5.75 - 0.321 \ln x$	.21	46.7 (f = 2, 46)	99
Residue (R)						
	$(NH_4)_2HPO_4$ (DAP)	9	$y = 158 + 35.0x$	.99		
	$(NH_4)_2SO_4$ (AS)	17	$y = 7.32 + 2.81x$	.49		
	Pooled	26	$y = 189 - 4.73x$	.02	1726 (f = 2, 22)	99

[1/] Test for the reduction in variance between the pooled and unpooled models.

[2/] All regressions significant at the 5 percent level or better.

Table 3.--*Regression equations for rate of spread, rate of weight loss, and residue*

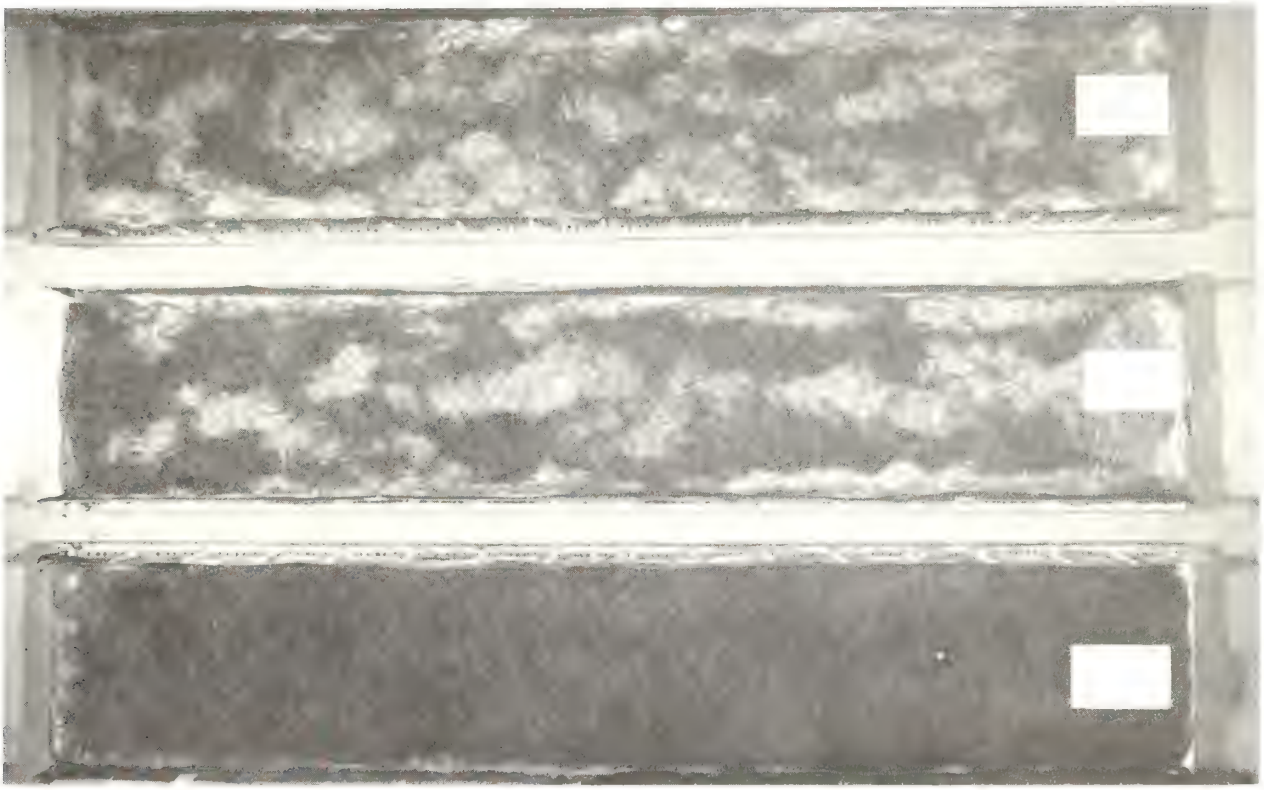


Figure 15.--Pine excelsior residue for (top to bottom) untreated, 7.5 percent $(NH_4)_2SO_4$, and 7.5 percent $(NH_4)_2HPO_4$ treated fuel beds.

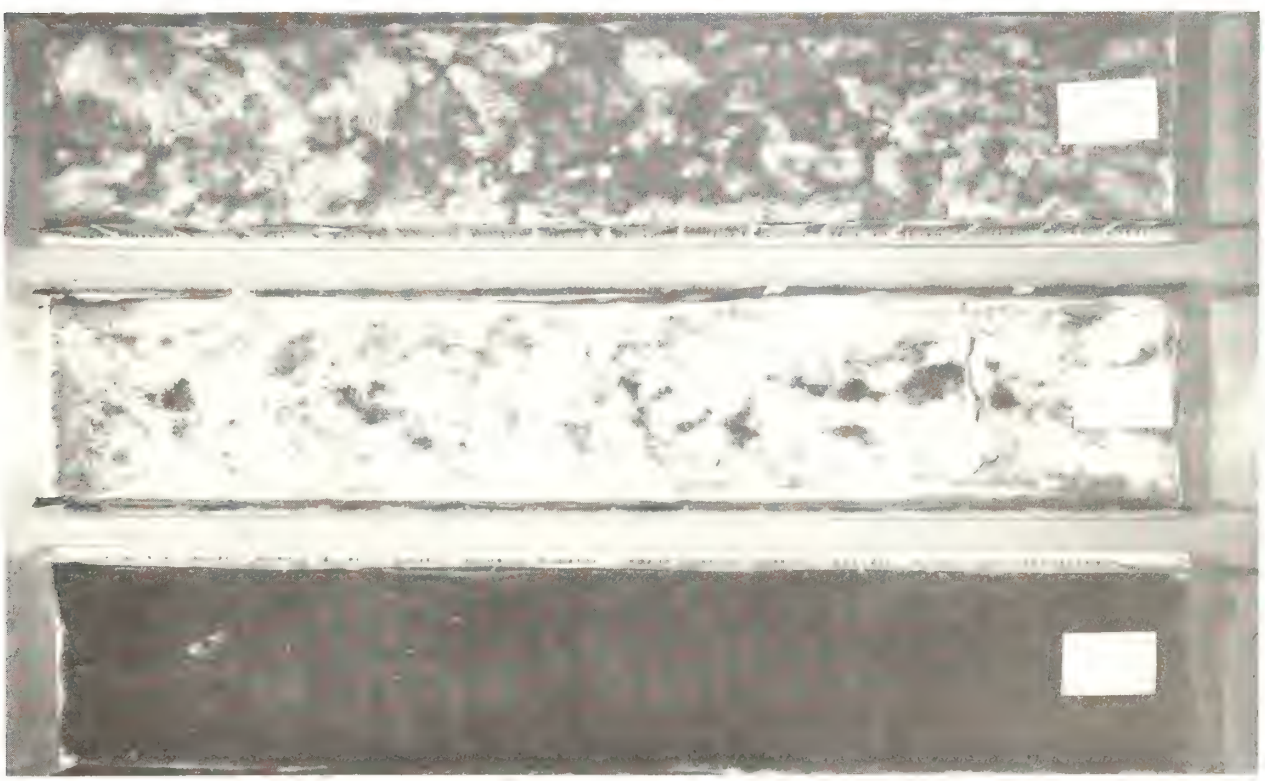


Figure 16.--Aspen excelsior residue for (top to bottom) untreated, 7.5 percent $(NH_4)_2SO_4$, and 7.5 percent $(NH_4)_2HPO_4$ treated fuel beds.

DISCUSSION

When attempting to characterize the effects of retardant chemicals on flammability, the measurement of three parameters provides a more complete picture than does the use of a single parameter. For example, the study has shown that chemicals can have similar effects on the rate of fire spread while having greatly different effects on the energy release rate and residue. Since retardant chemicals are used primarily to reduce both the combustion rate and the ability of the fire to propagate itself, it is necessary that these parameters be quantified to completely evaluate a retardant's effects on flammability.

For purposes of discussion, the effects a chemical has on flammability can be grouped under two primary considerations:

1. The effect the chemical has on flaming combustion, and

2. The effect the chemical has on glowing combustion.

Previous studies (George and Susott 1971) have indicated that the different effects ammonium phosphate and sulfate have on pyrolysis and combustion of cellulose are due to availability of the inorganic fraction involved in the reaction or to a different mechanism by which these chemicals alter pyrolysis and combustion. The results of this study indicate that although there are significant differences in the effects ammonium sulfate and phosphate have on flaming combustion, the differences in their effects on glowing combustion are much greater. It is theorized that the difference in the effects these chemicals have on glowing combustion is due to a difference in the availability of the inorganic fraction or retardant chemical. Figure 17 shows thermal decomposition curves for ammonium sulfate and ammonium phosphate.[2] The curves show that ammonium sulfate has completely decomposed by about 425° C. while ammonium phosphate decomposition is not complete until about 675° C. This suggests that by the time the fire has spread through an ammonium sulfate treated bed, and prior to the majority of the glowing combustion process, the ammonium sulfate may have decomposed. If this were true, the

[2]Figure 17 is taken from the paper by George and Susott (1971).

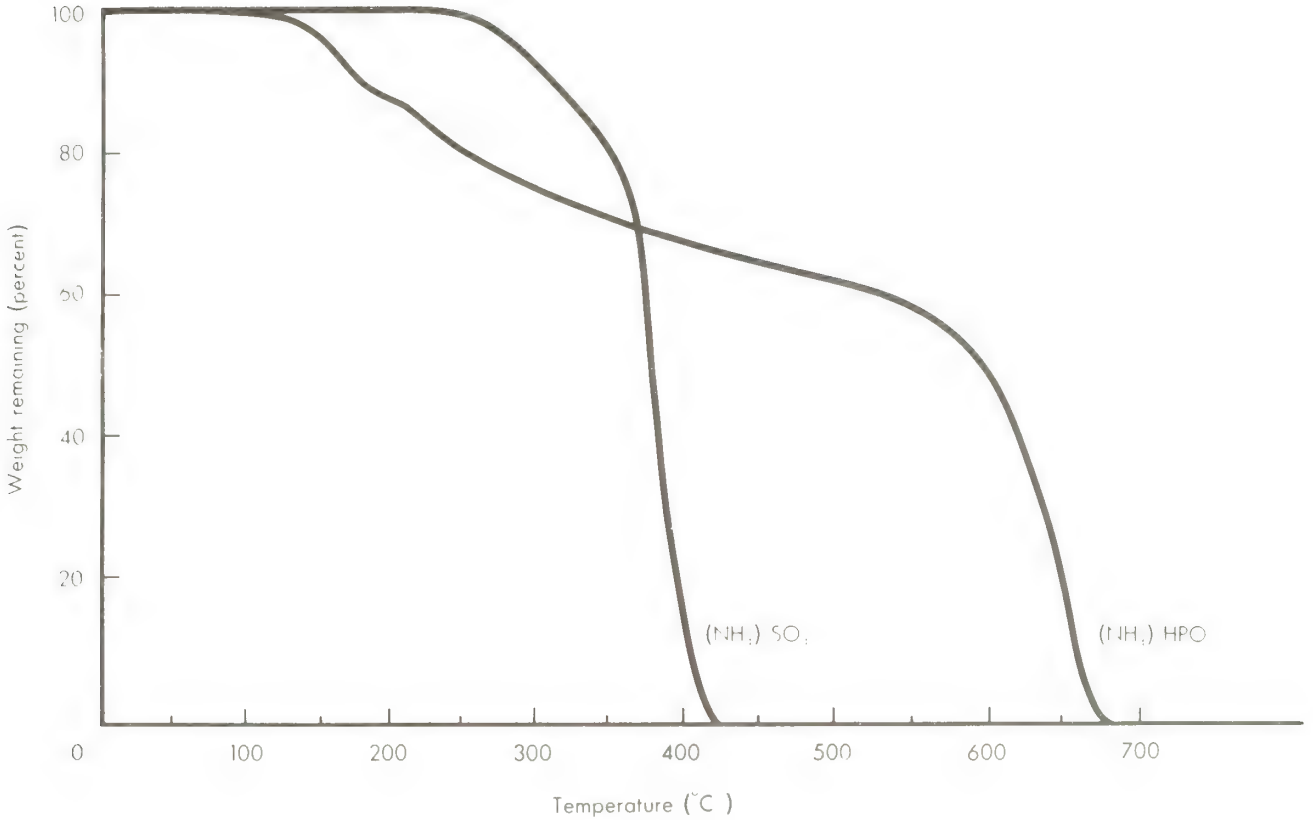


Figure 12.--Thermal decomposition curves for $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ heated at 15° C./min. in a flow of 1 liter/min. air.

ammonium sulfate would affect the glowing combustion process very little. Ammonium phosphate, on the other hand, might still be present, altering glowing combustion as well as flaming combustion. This would explain why these two chemicals affect glowing combustion in different ways. This does not mean that the chemicals' effects are necessarily different because of physical degradation differences. The difference may be a chemical difference and still depend on the amount of chemical available to enter into the reaction.

Anderson (1969), using ponderosa pine needle fuel beds, similar to those of this study, found the average temperature within the combustion zone to be 867° C. Considering a reduction in these temperatures because of treatment and durational differences between temperatures measured in the combustion zone and those determined during thermal analysis, it is likely that most of the ammonium sulfate would decompose during passage of the flame front.

The effects other chemicals have on flammability can be evaluated by using the regression equations which quantify the effects of ammonium phosphate and sulfate on flammability. These relationships can be used as standards by which the effect of typical forest fire retardant additives such as thickening agents, coloring agents, and corrosion and spoilage inhibitors, can be judged.

These data can also provide the basis for linking some of the more basic pyrolysis and combustion data concerning the effects of fire retardant chemicals with actual controlled open combustion laboratory tests.

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APPENDIX

Table 5.--*Summary of test data for $(NH_4)_2HPO_4$ treated ponderosa pine needle fuel beds*

Fire number	Treatment solution (chemical by weight)	Chemical applied			Dry fuel weight	Fire characteristics			Residue	
		Solution	Anhydrous chemical	Anhydrous chemical/ft.^{2}		Rate of spread	Rate of weight loss	Energy release rate	Grams	Percent increase over untreated
	Percent	Grams	Grams	Grams/ft.^{2}	Percent	R_s(ft./min.)	R_w(g./min.)	E(B.t.u./min.)		
2.5 A	2.5	975	24.4	2.03	0.97	1.46	223	4,299		
2.5 B	2.5	965	24.1	2.01	0.96	1.68	233	4,492		
2.5 C	2.5	955	23.9	1.99	0.95	1.55	202	3,895		
2.5 D	2.5	1,000	25.0	2.08	0.99	1.70	196	3,779	510	70.0
5.0 A	5.0	1,035	51.8	4.31	2.05	1.53	205	3,952		
5.0 B	5.0	995	49.8	4.15	1.98	1.27	160	3,085	560	86.7
5.0 C	5.0	990	49.5	4.12	1.96	1.08	169	3,258	540	80.0
5.0 D	5.0	1,000	50.0	4.17	1.99	1.26	184	3,548	565	88.3
5.0 E	5.0	980	49.0	4.08	1.94	1.39	191	3,682	530	76.7
7.5 A	7.5	1,000	75.0	6.25	2.98	1.36	180	3,470		
7.5 B	7.5	1,010	75.8	6.31	3.00	1.21	164	3,162		
7.5 C	7.5	975	73.1	6.09	2.90	1.25	200	3,856		
7.5 D	7.5	1,025	76.9	6.41	3.05	0.93	170	3,278	635	112.0
10.0 A	10.0	1,020	102.0	8.50	4.05	0.82	163	3,143		
10.0 B	10.0	995	99.5	8.29	3.95	0.69	174	3,355		
10.0 C	10.0	1,055	105.5	8.79	4.19	0.75	161	3,104		
10.0 D	10.0	1,010	101.0	8.42	4.00	0.94	196	3,779	630	110.0
12.5 A	12.5	1,010	126.2	10.52	5.01	0.69	131	2,526		
12.5 B	12.5	965	120.6	10.05	4.79	0.70	147	2,834	685	128.3
12.5 C	12.5	1,050	131.2	10.94	5.21	0.43	111	2,140	630	110.0
12.5 D	12.5	1,005	125.6	10.47	4.99	0.33	79	1,523	685	128.3
15.0 A	15.0	1,025	153.8	12.81	6.10	0.28	77	1,485		
15.0 B	15.0	960	144.0	12.00	5.71	0.68	137	2,641	660	120.0
15.0 C	15.0	1,000	150.0	12.50	5.95	0.50	129	2,487	730	143.3
15.0 D	15.0	990	148.5	12.38	5.90	0.35	101	1,947	725	141.7
17.5 A	17.5	1,050	183.8	15.31	7.29	0.26	71	1,369		
17.5 B	17.5	980	171.5	14.29	6.80	0.37	94	1,812	770	156.7
17.5 C	17.5	1,015	177.6	14.80	7.05	0.39	97	1,870	760	153.3
17.5 D	17.5	1,025	179.4	14.94	7.11	0.38	79	1,523	779	159.7
20.0 A	20.0	1,005	201.0	16.75	7.98	0.33	76	1,465	785	161.7
20.0 B	20.0	1,038	207.6	17.30	8.24	0.24	63	1,215	809	169.7
20.0 C	20.0	1,081	216.2	18.02	8.58	0.29	97	1,870	742	147.3

Table 6.--*Summary of test data for $(NH_4)_2SO_4$ treated ponderosa pine fuel beds*

Fire number	Treatment solution (chemical by weight)	Chemical applied				Fire characteristics			Residue	
		Solution	Anhydrous chemical	Anhydrous chemical/ft.^{2}	Dry fuel weight	Rate spread	Rate of weight loss	Energy release rate	Grams	Percent increase over untreated
	Percent	Grams	Grams	Grams/ft.^{2}	Percent	R_s(ft./min.)	R_w(g./min.)	E(B.t.u./min.)		
2.5 A	2.5	1,050	26.3	2.19	1.04	1.52	217	4,184		
2.5 B	2.5	970	24.3	2.02	.96	1.50	228	4,396		
2.5 C	2.5	985	24.6	2.05	.98	1.52	225	4,338		
2.5 D	2.5	995	24.8	2.07	.99	1.76	217	4,184	340	13.3
5.0 A	5.0	1,015	50.8	4.23	2.01	1.31	218	4,203		
5.0 B	5.0	986	49.3	4.11	1.96	1.18	198	3,817	410	36.7
5.0 C	5.0	965	48.3	4.02	1.91	1.32	170	3,278	320	6.7
5.0 D	5.0	968	48.4	4.03	1.92	1.68	196	3,779	450	50.0
7.5 A	7.5	970	72.8	6.06	2.89	1.36	212	4,087		
7.5 B	7.5	980	73.5	6.13	2.92	1.05	158	3,046	505	68.3
7.5 C	7.5	1,000	75.0	6.25	2.98	1.06	162	3,123	442	47.3
7.5 D	7.5	1,045	78.4	6.53	3.11	1.22	180	3,470	391	30.3
10.0 A	10.0	1,030	103.0	8.58	4.09	0.92	210	4,049		
10.0 B	10.0	985	98.5	8.21	3.91	0.90	179	3,451		
10.0 C	10.0	1,045	104.5	8.71	4.15	0.98	195	3,760		
10.0 D	10.0	1,025	102.5	8.54	4.07	1.03	143	2,757	395	31.7
12.5 A	12.5	1,000	125.0	10.42	4.96	0.75	167	3,220		
12.5 B	12.5	953	119.1	9.93	4.73	0.72	156	3,008	465	55.0
12.5 C	12.5	925	115.6	9.64	4.59	0.89	197	3,798	385	28.3
12.5 D	12.5	1,005	125.6	10.47	4.99	0.90	165	3,181	422	40.7
15.0 A	15.0	958	143.7	11.98	5.70	0.56	118	2,275		
15.0 B	15.0	1,020	153.0	12.75	6.07	0.52	151	2,911		
15.0 C	15.0	995	149.3	12.44	5.92	0.54	143	2,757	468	56.0
17.5 A	17.5	1,020	178.5	14.88	7.09	0.56	156	3,008		
17.5 B	17.5	922	161.4	13.45	6.40	0.43	113	2,179	487	62.3
17.5 C	17.5	1,039	181.8	15.15	7.21	0.45	135	2,603	381	27.0
20.0 A	20.0	1,053	210.6	17.55	8.36	0.44	114	2,198	395	32.0
20.0 B	20.0	1,000	200.0	16.67	7.94	0.38	98	1,889	490	63.3
20.0 C	20.0	1,005	201.0	16.75	7.98	0.23	51	983	439	46.3

Table 7.--Summary of [illegible]

Fire number	Treatment solution (amt. of N (g. weight))	Chemical applied				Fire characteristics				Residue	
		Solution	Ammonia nitrogen	Anhydrous ammonia	Dry fuel weight	Rate of spread	Rate of weight loss	Energy release rate	Grass	Percent increase over control
	Number	Grams	Grams	Grams/ft.^{2}	lbs/ft.^{2}	ft./min.	lbs./ft.^{2}/min.	B.t.u./ft.^{2}/min.		
[illegible]	A	2.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	B	2.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	2.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	2.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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Table 8.--*Summary of test data for $(NH_4)_2SO_4$ treated aspen excelsior fuel beds*

Fire number	Treatment solution (chemical by weight)	Chemical applied				Fire characteristics			Residue	
		Solution	Anhydrous chemical	Anhydrous chemical/ft.^{2}	Dry fuel weight	Rate of spread	Rate of weight loss	Energy release rate	Grams	Percent increase over untreated
	Percent	Grams	Grams	Grams/ft.^{2}	Percent	R_s(ft./min.)	R_w(g./min.)	E(B.t.u./min.)		
2.5 A	2.5	995	24.9	2.07	1.47	3.78	340	6,355		
2.5 B	2.5	960	24.0	2.00	1.42	2.94	352	6,579		
2.5 C	2.5	940	23.5	1.96	1.39	3.48	296	5,532		
2.5 D	2.5	1,035	25.9	2.16	1.53	2.56	307	5,738	5	5
2.5 E	2.5	975	24.4	2.03	1.44	2.78	323	6,037	30	30
5.0 A	5.0	1,010	50.5	4.21	2.99	2.03	293	5,476		
5.0 B	5.0	985	49.3	4.10	2.91	1.04	233	4,355	15	15
5.0 C	5.0	950	47.5	3.96	2.81	2.08	321	5,999	10	10
5.0 D	5.0	970	48.5	4.04	2.87	1.10	222	4,149	5	5
7.5 A	7.5	995	74.6	6.22	4.41	1.02	211	3,944		
7.5 B	7.5	1,000	75.0	6.25	4.43	0.84	170	3,177	28	28
7.5 C	7.5	1,005	75.4	6.28	4.45	0.96	180	3,364	60	60
7.5 D	7.5	980	73.5	6.13	4.35	0.88	188	3,514		
10.0 A	10.0	1,060	106.0	8.83	6.26	0.84	182	3,402		
10.0 B	10.0	1,000	100.0	8.33	5.91	0.98	204	3,813		
10.0 C	10.0	1,030	103.0	8.58	6.09	1.10	219	4,093		
10.0 D	10.0	1,060	106.0	8.83	6.26	1.21	247	4,616	15	15
12.5 A	12.5	1,060	132.5	11.04	7.83	0.67	163	3,046		
12.5 B	12.5	1,080	135.0	11.25	7.98	0.90	177	3,308	65	65
12.5 C	12.5	990	123.8	10.31	7.31	0.87	175	3,271	25	25
12.5 D	12.5	1,008	126.0	10.50	7.45	0.67	167	3,121	22	22
15.0 A	15.0	985	147.8	12.31	7.31	0.72	152	2,841		
15.0 B	15.0	1,020	153.0	12.75	9.04	0.95	222	4,149		
15.0 C	15.0	970	145.5	12.13	8.60	1.11	218	4,074		
15.0 D	15.0	990	148.5	12.38	8.78	0.88	200	3,738	40	40
17.5 A	17.5	985	172.4	14.36	10.18	1.09	260	4,859		
17.5 B	17.5	1,028	179.9	14.99	10.63	0.55	125	2,336	28	28
17.5 C	17.5	1,026	179.6	14.96	10.61	0.62	199	3,719	56	56
20.0 A	20.0	1,050	210.0	17.50	12.41	0.66	135	2,523	65	65
20.0 B	20.0	1,005	201.0	16.75	11.88	0.92	190	3,551	57	57
20.0 C	20.0	980	196.0	16.33	11.58	0.88	200	3,738	55	55

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GEORGE, CHARLES W., and AYLMER D. BLAKELY

1972. Effects of ammonium sulfate and ammonium phosphate on flammability. USDA Forest Serv. Res. Pap. INT-121, 26 p., illus. Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401.

Pine needle and excelsior fuel beds treated with various amounts of $(NH_4)_2SO_4$ and $(NH_4)_2HPO_4$ were burned in an environmentally controlled wind tunnel. The two chemicals have different effects on the rate of fire spread, rate of weight loss or equivalent energy release rate, residue, and thus on flammability. The differences these chemicals have on glowing combustion phase are probably due to the difference in their thermal behavior and hence availability.

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HYDROGRAPH ANALYSIS: A COMPUTERIZED SEPARATION TECHNIQUE

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Abstract

Describes a computer program (Fortran IV language) designed to analyze hydrographs. Using only input data of stage and time, the program automatically determines the beginning and end of each event, analyzes each event with respect to all its hydrologic characteristics (including a partitioning of base flow, interflow, and rapid flow), and then prints a detailed analysis of each event and a series of summaries of all events analyzed. The hydrologist can influence the results only by changing the time interval between hydrograph readings. The method has been tested on both simple and complex hydrographs representative of runoff events in many regions of the United States.

INTRODUCTION

A hydrograph is a curve depicting a stream's rate of flow throughout a given period of time. If the records are complete, the curve is continuous; this curve reveals to the trained observer the innermost secrets of a watershed's behavior — nothing is concealed. Every change in the curve reflects the watershed's reaction to a multitude of internal and external forces. A steep rise in the curve could reflect the passage of a high intensity storm; a gradual descent might reflect the watershed's high water storage capacity. Every change in the hydrograph can be readily interpreted in the light of forces acting on the watershed. A study of all changes in the hydrograph is a key to our understanding of the functioning of a watershed.

Streamflow is one of the end products of precipitation that falls on a watershed. Some of this precipitation falls directly into the stream channel and brings about an immediate rise in the rate of streamflow. Similarly, another portion of the precipitation quickly enters well defined channels; it also contributes to the rapid rise in streamflow rate. Some of the rain enters the soil mantle, and thence, by circuitous paths, finally enters the stream channel. Another portion, pulled by the force of gravity, finds its way to the water table (the surface of the groundwater), and eventually flows into the stream channel. The shape of the hydrograph is determined by the amount and rate at which each of these components enters the stream channel. This shape is a unique expression of a watershed's reaction to its environment.

Although the ultimate purpose of hydrograph analysis is an understanding of a watershed's behavior, this can be achieved only if we have a thorough understanding of the flow patterns that together make up the hydrograph. For this reason, hydrologists have devised many methods to separate the components, despite the belief that "it is practically impossible to measure the volumes of water following each path . . . ."[1]

The first and most important step in hydrograph analysis is to partition the hydrograph into its components:

Total flow = Base flow + Interflow + Rapid flow

Base flow is the contribution from groundwater — water that moves under differences in head in a saturated zone. Interflow is water that percolates through the soil mantle and, after some delay, enters the stream. Rapid flow (also called surface flow) is water that enters the stream channel with a minimum delay; it includes channel interception. The sum of interflow and rapid flow are designated as stormflow.

The techniques now employed in hydrograph analysis are highly subjective. Moreover, the analyst starts his analysis at the end of the storm hydrograph and proceeds backwards in time towards the beginning of the storm hydrograph.[2] Linsley and others discuss thoroughly the procedures and arbitrary rules that are used in hydrograph separation.

This paper presents a computer program designed to analyze automatically hydrologic

[1] *Ray K. Linsley, Jr., Max A. Kohler, and Joseph L. H. Paulhus. P. 387, in: Applied Hydrology, 689 p. New York: McGraw-Hill Co. 1949.*

[2] *Ibid, Ch 15.*

events recorded on a hydrograph. These events could result from either, or a combination of, rainstorms, snowmelt, or excessive evapotranspiration. The analytical technique is completely automated; the results are dependent entirely on the flow rates shown on the hydrograph. The hydrologist can influence the results in only one way: by increasing or decreasing the number of sampling points along the hydrograph.

The technique used in the computer program was tested on hydrographs of typical runoff events in many regions in the United States; it was considered successful because the computed separation curves crossed the recession limbs of the hydrographs at their points of inflection.

BASIC ASSUMPTIONS

Two basic assumptions underlie the computations: that both increment in base flow and the ratio of surface runoff to interflow depend essentially on the hydrograph's rate of rise. A rapid rise indicates a proportionately smaller increment in base flow than does a moderate rise. On the other hand, the ratio of surface runoff to interflow is large when the stream rises rapidly; this ratio is small when the stream rises slowly.

We also assume that (a) surface runoff (including channel interception) ends at the first inflection point following peak flow, and that (b) interflow ends at the lower inflection point on the recession limb of a simple hydrograph. Our research was directed towards defining equations that — if based on the first two assumptions — would meet the criteria of the third and that would be applicable to any hydrograph.

ESSENTIAL ELEMENTS OF THE SEPARATION TECHNIQUE

The heart of this program consists of a series of calculations to determine the consecutive positions of points along two curves: the base flow curve (which separates base flow from stormflow) and the interflow curve (which separates interflow from rapid flow.) Figure 1 is used to illustrate the parameters entering the calculation of points along both the base flow and interflow lines.

Base Flow Computations

The rate of flow at any point (P_i) on the base flow line is equal to the sum of the rate at a prior time (P_{i-1}) plus an incremental value (U_i):

$$P_i = P_{i-1} + U_i \qquad (1)$$

where

$$U_i = \exp[-(1.0+\sin A)]\times(\Delta t \times \Delta R \times \tan B)^{1/2} \qquad (2)$$

where (see fig. 1)

$$\Delta R = R_i - P_{i-1}$$
$$\Delta t = t_i - t_{i-1}$$
$$A = \arctan(\Delta R/\Delta t)$$
$$B = (H \times A - \Delta R)/H$$
$$H = (\Delta R^2 + \Delta t^2)^{1/2}$$

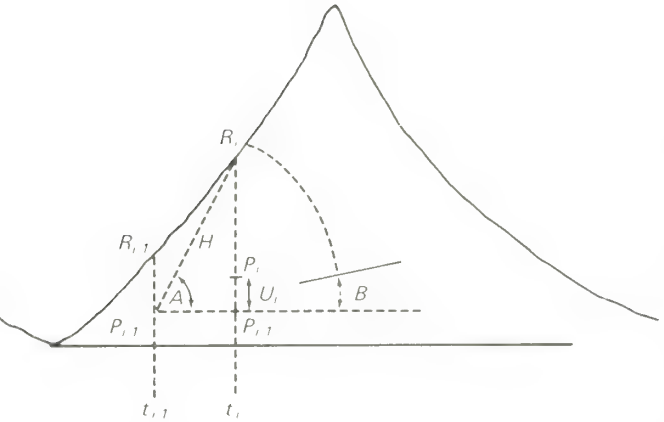

Figure 1. — Parameters used to locate points along the base flow line.

Each successive point on the hydrograph is the basis for a new calculation of P_i. The event ends when the value of a point on the base flow line equals a rate value on the hydrograph trace; i.e., $P_i = R_i$. The next hydrograph event begins when the hydrograph starts to rise again. At that point, $R_{i-1} = P_{i-1}$.

Interflow Computations

The curve that separates interflow from surface flow (which includes channel interception) is similarly computed from point to point. Any point S_i on the interflow curve is equal to the value at a prior time (S_{i-1}) plus an incremental value (W_i).

Thus,
$$S_i = S_{i-1} + W_i \qquad (3)$$

where

$$W_i = |(\Delta t^2 + \Delta S^2)^{1/2} \times \Delta S| / (\Delta t + K \times \Delta S) \qquad (4)$$

where

$$\Delta t = t_i - t_{i-1}$$
$$\Delta S = R_i - S_{i-1}$$
$$K = 3.0$$

Surface runoff ends when the curve intersects the hydrograph; i.e., $S_i = R_i$.

DISCUSSION OF TECHNIQUE

Table 1 shows the results of analyses of hydrographs of representative storms in several regions of the United States. The analyzed hydrographs include both simple and complex hydrographs. Source for the basic hydrograph data is Hobbs and Burford.[3] In all cases, the analyses were performed on data expressed in cubic feet per second (c.f.s.). Data originally expressed in inches per hour were converted to c.f.s. Figures 2 and 3 show the separation, respectively, of a simple and complex hydrograph into its components. The figures show the total flow hydrograph, and the computed interflow and base flow rates.

Normally, on large watersheds, the time interval between sampled points on the hydrographs is one or more hours. Therefore, the analytical results will be independent of the hydrologist. On very small watersheds, the hydrologist tries to reproduce the shape of the hydrograph by sampling at small and variable increments of time because the smaller the time interval used the more accurately can he reproduce the hydrograph's original shape. Thus, on very small watersheds the hydrologist can influence the results by increasing or decreasing the number of sampling points used to reproduce the shape of the hydrograph.

Our analyses show that when we reduced the number of sampling points 75 percent, we changed the computed results by significant amounts. The maximum change was observed on a small watershed (0.07 km.^{2}) from which all runoff ceased after 1.75 hours: computed total flow was increased 0.457 cm. (28 percent); stormflow increased 0.508 cm. (28 percent); and stormflow runoff duration was increased 6.6 minutes. Consequently, the hydrologist who analyzes the hydrographs of

[3] *Harold W. Hobbs and James B. Burford. Hydrologic data for experimental agricultural watersheds in the United States, 1963. USDA Agr. Res. Serv., Misc. Pub. 1164. 1970.*

Table 1. — Analysis of hydrographs of streams in different regions of the United States[1]

	Vero Beach, Florida	Blacksburg, Virginia	N. Danville, Vermont	Hastings, Nebraska	Colby, Wisconsin	Waco, Texas	Reynolds, Idaho
Area (km.^{2})	255.5	6.0	111.1	8.3	1.4	2.3	233.4
			PERCENT OF TOTAL FLOW				
Base flow	32.47	14.80	53.16	9.07	22.74	5.52	13.36
Stormflow	67.53	85.20	46.84	90.93	77.26	94.48	86.64
			PERCENT OF STORMFLOW				
Interflow	65.38	89.99	90.62	66.58	90.41	89.63	93.49
Surface flow	34.62	10.01	9.38	33.42	9.59	10.37	6.51
Before peak	44.19	32.47	37.81	39.92	14.59	26.71	14.68
After peak	55.81	67.53	62.19	60.08	85.41	72.39	85.32
			DURATION (HOURS) OF STORMFLOW				
Time to peak	48.00	1.00	10.08	3.17	4.12	1.23	18.00
Recession time	56.64	3.36	24.88	5.91	8.87	3.89	38.60
Total time	104.64	4.36	34.96	9.08	12.99	5.12	56.60

[1] *Source of data ibid, text footnote 3.*

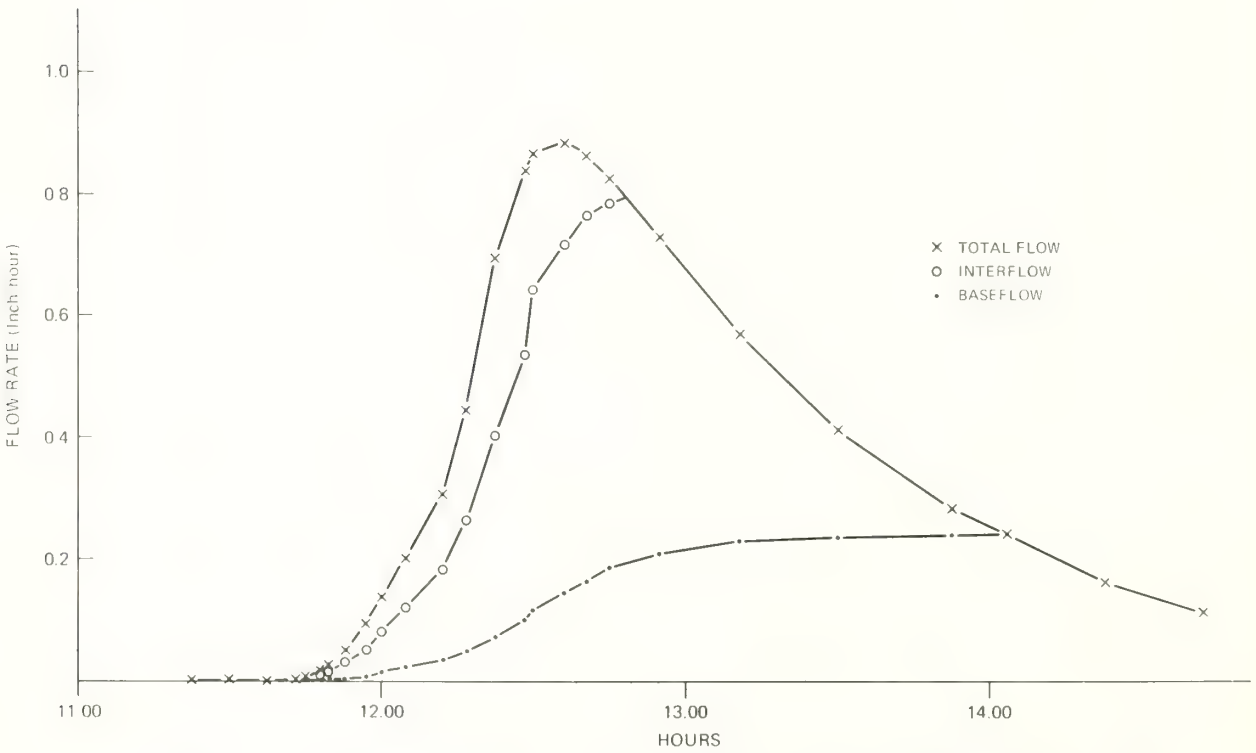

Figure 2. — Flow components in a simple hydrograph recorded at Riesel, Texas.

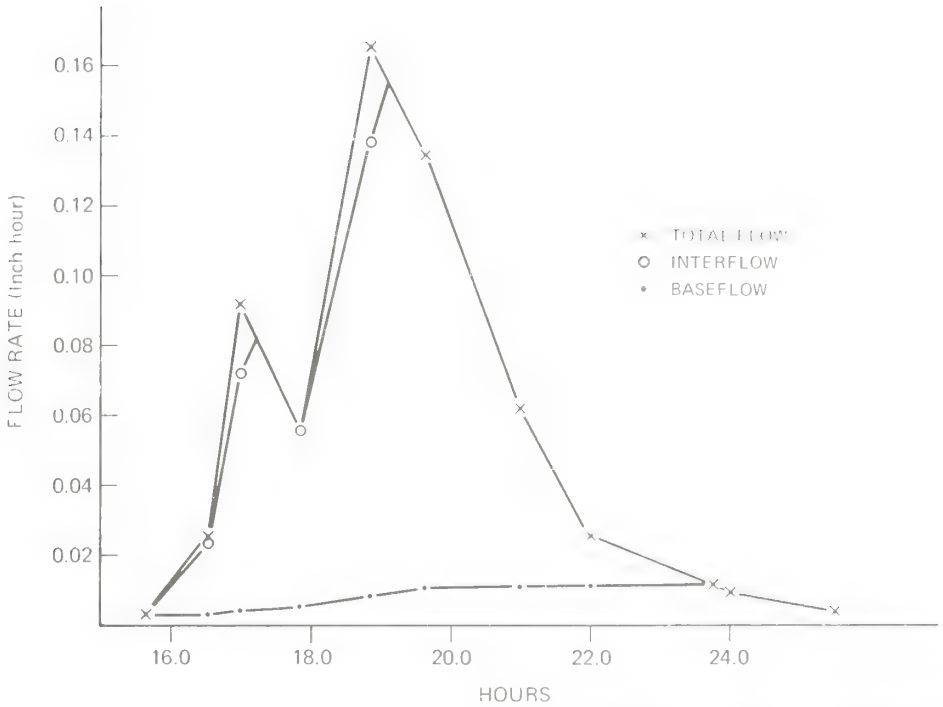

Figure 3. — Flow components of a complex hydrograph recorded at Hastings, Nebraska.

very small watersheds should make every effort to select points that reproduce as accurately as possible the true shape of the hydrograph.

Equation (2) includes two angle measurements (*A* and *B*). Accordingly, it is apparent that the results of any analysis will depend on the units of measurement, as shown in table 2.

Normally, the analysis would be performed on data expressed in a unit suitable for the watershed: c.f.s. for low water-yielding watersheds, and inch/hour for high water-yielding drainages. Certainly, a great deal of accuracy is lost when calculations are performed on angles measured in minute fractions of a radian. For example: suppose streamflow from a 580-acre (2.346-km.^{2}) watershed is expressed in inches. If the increase is 0.0005 inch in 0.1 hour, angle *A* is approximately 0.005 radian; if expressed in c.f.s., the angle is 1.24 radians. The effect of loss in accuracy as well as the unit of measurement is fully reflected in the last column of table 2, which shows figures for surface runoff based on data expressed in inch/hour.

Equation (4) is used to partition stormflow into surface runoff (including channel interception) and interflow. The equation contains a constant (*K*) to which we assigned a value of 3.0. The exact value of *K* can be determined only if precise data from controlled laboratory or field experiments are available, but we do not have such data.

A change in the value of *K* results in significant changes in the analytical results (table 3). Increasing the value of *K* yields (a) larger computed values for surface runoff; (b) a corresponding decrease in interflow; and (c) a larger computed value for duration of surface runoff. Our analyses for large forested watersheds show that the computed period for surface runoff duration is extended by 1-3 hours if the value of *K* is increased from 3.0 to 4.0.

We believe that the value of *K* is related to the proportion of the watershed represented by the main channel and its tributaries. For any particular watershed, the value of *K* might well change with either or both the season and the characteristics of the storm. This concept of *K* agrees with the concept of a variable source area.[4]

[4] *John D. Hewlett and Alden R. Hibbert. Factors affecting the response of small watersheds to precipitation in humid areas. P. 275-290, in: Forest Hydrology, edited by William E. Sopper and Howard W. Lull. New York: Pergamon Press, Inc. 1967.*

The assigned value of $K = 3.0$ is acceptable if the hydrologist is mainly interested in the comparative behavior of several watersheds or in the reaction of a single watershed to storms of different magnitude. On the other hand, the precise partitioning of stormflow into surface runoff and interflow will depend on the exact value of K as determined under controlled experiments.

Table 2. — Effect of unit of measurement on results of analysis

Location	Basic hydrograph unit		Basic hydrograph unit	
	c.f.s.	inch/hr.	c.f.s.	inch/hr.
	Stormflow as % of total runoff		*Surface runoff as % of stormflow*	
Vero Beach, Fla.	67.53	69.80	34.62	0
Blacksburg, Va.	85.20	60.01	10.01	7.89
N. Danville, Vt.	46.84	82.54	9.38	0
Hastings, Neb.	90.93	87.19	33.42	8.14
Colby, Wisc.	77.26	75.12	9.59	0.78
Waco, Tex.	94.48	66.30	10.37	17.99
Reynolds, Ida.	86.64	59.31	6.51	0.37

Table 3. — Effect of K (Equation 4) on surface runoff as percent of stormflow during October-November 1968, in the East Fork Horse Creek watershed, Idaho

Event No.	Stormflow	$K = 2$	$K = 3$	$K = 4$	$K = 5$
	Cubic ft./100				
19	6.7	5.77	8.60	11.33	13.96
4	22.5	1.70	2.55	3.40	4.24
3	68.8	2.17	3.34	4.55	5.81
23	98.9	3.64	5.36	7.10	8.90
1	202.6	0.26	0.38	0.49	0.60
15	308.4	1.54	2.44	3.44	4.53
34	613.2	11.93	18.53	24.63	30.15
28	1873.1	11.79	19.65	27.05	33.63
16	3898.0	11.89	19.95	27.10	33.24

THE COMPUTER PROGRAM

The program consists of three sections: Input of basic data (lines 1 through 12); analysis of data (lines 13 through 129); and output of results (lines 130 through 183).

Input of Basic Data

The program is designed to accommodate data for 1 year, providing the time interval between readings is not less than 1 hour and the number of storm events is not more than 300. The dimension statements should be changed if the number of data points exceeds 9000 or the number of anticipated storm events exceeds 300. If either of these conditions applies, the author suggests that less than a year's data be analyzed at one time.

The "read" statement should fit the format in which the input data are punched on the cards. In this program, there is no "read" statement for *hour*, because all hydrograph readings were taken at 1-hour intervals. If a variable time interval characterizes the input data, then a new "read" statement should be made.

Analysis of Data

1. Volume parameters
   - Total flow
     - Base flow
     - Storm flow
       - Interflow
       - Rapid flow
2. Time parameters
   - Hour at which event starts
   - Hour at which event peaks
   - Hour at which event ends
   - Number of hours from start to peak
   - Number of hours from peak to end (recession time)
3. Rate parameters
   - Initial streamflow rate
   - Peak rate
   - Final rate
4. Angle parameters (in radians)
   - Rising angle (formed by intersection of horizontal line and line connecting initial and peak rates)
   - Recession angle (formed by intersection of a vertical line and line connecting peak and final rates)
   - Top Angle (formed by intersection of line connecting initial and peak rates with line connecting peak and final rates)
   - Base angle (formed by intersection of horizontal line and line connecting initial and final rates)
5. Line parameters
   - Base line (length of line connecting initial and final points of the storm hydrograph)
   - Perimeter (sum of lines connecting initial, peak, and final points on the storm hydrograph.)
6. Ratio parameter
   - Ratio of perimeter to natural logarithm of 1.0 + stormflow)

The relation between stage and flow rate (cubic feet per second) is unique to each type of waterflow-measuring installation. Hence, the user of this program must supply the calibration equation that applies to the installation. This is done in lines 23 and 24, and also in lines 38, 39, and 56. In addition, the user must indicate the area of the watershed in acres (line 164).

Output of Results

Summaries of results of all analyzed storms are tabulated in a series of tables (see Appendix 1) and also on cards. (See Appendix 2, lines 173 and 174, for format.)

Appendix tables 1 through 5 are examples of the program printout. Tables 2-5 are summary tables of all the storms analyzed. Table 1 (Appendix 1) is a detailed analysis of each individual event, and requires some explanation. The sample printout is an analysis of a short storm during October 1968 on the East Fork of Horse Creek in north central Idaho.

The storm started at hour 347 when streamflow rate was 4.139818 c.f.s. (Six decimals are printed to enable the hydrologist to analyze any portion of the event without loss of accuracy due to rounding-off procedures.) The storm ended at hour 361.92 when streamflow rate was 4.335419 c.f.s. Column 2 shows the rate of flow (c.f.s.) at hourly intervals along the base flow line — the line separating base flow from stormflow. The third column ("runoff rate") shows actual streamflow rate (c.f.s.) at hourly intervals. This figure is the input data (stage-in feet) converted to c.f.s. The last column (interflow rate) shows the rate of flow (c.f.s.) at hourly intervals along the line separating interflow from rapid flow. As long as values in this column are *smaller* than those in the "runoff rate" column, the rapid flow separation curve has not crossed the hydrograph. When rapid flow has ended, then the figures in the last column are identical with those in the "runoff rate" column. In this example, rapid flow ended between hours 353 and 354. Total flow from hour 347 to hour 361.92 was 68.413391 c.f.s.-hours (column 5), of which 63.696930 was base flow (column 4) and 4.716461 was stormflow (column 7). Stormflow amounted to 6.89 percent of the total flow (column 6). Other figures in table 1 as well as in the summary tables are self explanatory.

USES FOR THE COMPUTER PROGRAM

Hydrograph analysis is a difficult and time-consuming operation. The inherent difficulties have forced hydrologists to limit their analysis to a few extraordinary hydrologic events, or to events that they believe represent average conditions.

By using this computer program, the hydrologist can analyze all streamflow events — rainstorms, snowmelt events, and even daily events resulting from excessive evapotranspiration. Any event, regardless of its cause, can be analyzed automatically, and can be recorded in a condensed form. The computer program enables the hydrologist to readily compare the numerous elements of hydrologic events occurring on two or more watersheds, because they are recorded in orderly form.

APPENDIX 1

Tables 1 through 5 are examples of the printed output of the program. Table 1 is an analysis of storm No. 6. Tables 2 through 5 are summary tables of 34 storms, which include storm No. 6.

TABLE 1

STORM NUMBER 6

STORM BEGINS AT 347.00 INITIALRUNOFF RATE IS 4.139818

TIME	BASEFLORATE	RUNOFRATE	BASEFLO	TOTALFLO	STORMFLO%	STORMFLO	INTERFLO	RAPIDFLO	INTERFLORATE
348.00	4.141055	4.235245	4.140436	4.187531	1.124695	0.047095	0.036644	0.010451	4.214343
349.00	4.155521	4.526405	8.288724	8.568357	3.263565	0.279633	0.187118	0.092515	4.383182
350.00	4.174996	4.625076	12.453982	13.144097	5.250397	0.690115	0.477149	0.212966	4.527397
351.00	4.208504	4.875252	16.645721	17.894257	6.977310	1.248535	0.902907	0.345628	4.707621
352.00	4.246061	4.976706	20.873001	22.820221	8.532883	1.947220	1.460339	0.486881	4.861808
353.00	4.281388	4.976706	25.136719	27.796921	9.570145	2.660202	2.101425	0.558777	4.947815
354.00	4.305362	4.824818	29.430084	32.697678	9.993362	3.267593	2.694366	0.573227	4.824818
355.00	4.316115	4.625076	33.740814	37.422623	9.838470	3.681808	3.108575	0.573234	4.625076
356.00	4.323717	4.575636	38.060730	42.022964	9.428741	3.962234	3.389014	0.573220	4.575636
357.00	4.326726	4.477373	42.385941	46.549469	8.944321	4.163528	3.590297	0.573232	4.477373
358.00	4.329628	4.477373	46.714111	51.026840	8.451904	4.312729	3.739492	0.573236	4.477373
359.00	4.332428	4.477373	51.045135	55.504211	8.033798	4.459076	3.885838	0.573238	4.477373
360.00	4.335131	4.477373	55.378906	59.981583	7.673492	4.602676	4.029431	0.573245	4.477373
361.00	4.335418	4.379911	59.714172	64.410217	7.290894	4.696045	4.122799	0.573246	4.379911
361.92	4.335419	4.335419	63.696930	68.413391	6.894089	4.716461	4.143235	0.573226	4.335419

TABLE 2

SUMMARY OF STORM DATA

NO	TIME START	TIME PEAK	TIMEEND	R START	R PEAK	R END	STORMFLO	INTERFLO	RAPIDFLO
1	69.0000	118.0000	144.1334	2.4500	2.6077	2.5179	5.6283	5.6071	0.0212
2	165.0000	201.0000	246.7191	2.1088	2.5284	2.3449	10.7387	10.6851	0.0536
3	254.0000	278.0000	291.4971	2.3341	9.8412	6.3394	90.8405	77.1339	13.7066
4	301.0000	303.0000	308.6111	5.1820	5.2858	5.1908	0.6245	0.6086	0.0159
5	327.0000	331.0000	345.2043	4.1398	4.3799	4.1777	1.9108	1.8470	0.0638
6	347.0000	352.0000	361.9185	4.1398	4.9767	4.3354	4.7165	4.1432	0.5732
7	393.0000	422.0000	433.2788	3.2317	3.8124	3.5274	9.3303	9.0223	0.3080
8	443.0000	472.0000	479.4075	3.1885	6.7616	4.5090	27.3900	22.0784	5.3115
9	480.0000	481.0000	562.4644	2.9760	5.1304	4.6021	36.3999	32.9199	3.4800
10	568.0000	572.0000	582.0872	4.5756	4.8753	4.6208	1.6851	1.6027	0.0824
11	591.0000	604.0000	611.7495	4.4774	6.0339	5.0023	10.9402	9.8133	1.1268
12	666.0000	667.0000	673.9541	4.1398	4.1874	4.1420	0.3234	0.3174	0.0060
13	690.0000	701.0000	722.6267	4.0024	4.6747	4.3496	7.2463	6.7678	0.4785
14	779.0000	782.0000	836.1768	3.5847	3.6752	3.6219	3.7770	3.7662	0.0108
15	890.0000	901.0000	916.9890	2.6077	3.2750	2.9356	8.5678	8.3585	0.2093
16	918.0000	942.0000	953.9739	2.9342	14.8462	7.0009	108.2775	86.6776	21.5999
17	957.0000	958.0000	959.4570	6.4219	6.8189	6.4540	0.6103	0.3771	0.2332
18	996.0000	1010.0000	1024.3865	5.0277	7.3424	5.8496	16.6890	13.7689	2.9201
19	1035.0000	1037.0000	1038.2371	5.3380	5.4429	5.3410	0.1861	0.1701	0.0160
20	1042.0000	1044.0000	1046.3083	5.1820	5.2858	5.1860	0.2856	0.2697	0.0159
21	1047.0000	1049.0000	1049.4941	5.0790	5.2858	5.0870	0.2005	0.1553	0.0452
22	1050.0000	1051.0000	1051.9805	4.8753	5.0277	4.8782	0.1481	0.1019	0.0462
23	1053.0000	1059.0000	1066.1768	4.8753	5.3380	4.9588	2.7460	2.5989	0.1472
24	1067.0000	1068.0000	1072.9065	4.8753	5.0277	4.8847	0.5714	0.5191	0.0523
25	1080.0000	1137.0000	1143.0048	4.0452	11.4696	9.1180	102.8784	90.2168	12.6616
26	1162.0000	1195.0000	1207.2866	4.4285	5.6018	5.0131	14.7247	14.3110	0.4137
27	1213.0000	1217.0000	1226.3235	4.8753	5.1304	4.9247	2.0130	1.9556	0.0574
28	1238.0000	1253.0000	1267.4221	4.7245	10.8479	7.0589	52.9298	41.8076	10.2222
29	1305.0000	1311.0000	1326.2224	5.5487	6.4780	5.7924	5.9913	5.3071	0.6742
30	1373.0000	1374.0000	1374.9824	5.3904	5.4429	5.3908	0.0520	0.0449	0.0071
31	1388.0000	1389.0000	1391.4775	5.2858	5.3904	5.2908	0.2789	0.2526	0.0262
32	1399.0000	1400.0000	1400.4393	4.3315	4.3799	4.3322	0.0320	0.0279	0.0041
33	1401.0000	1407.0000	1416.1445	4.2352	5.3904	4.6037	7.6906	6.7187	0.9719
34	1421.0000	1428.0000	1452.3252	3.9982	5.5344	4.8085	17.0336	13.8773	3.1563

TABLE 3

STORM NO	STORMFLO BASE LINE	PERIMETER	TOP ANGLE	TIME TO PEAK	STORMFLO	PERIMETER/ LN(1+STORMFLO)	RECESSION TIME	BASE LINE ANGLE	RISING LIMB ANGLE	FALLING LIMB ANGLE
1	75.133377	150.267151	3.134936	49.000000	5.628342	79.449478	26.133362	0.000904	0.003219	1.567360
2	81.719391	163.441254	3.125924	36.000000	10.738663	66.361618	45.719055	0.002889	0.011654	1.566782
3	37.710373	76.800995	2.584583	24.000000	90.840500	16.991165	13.497070	0.106411	0.303153	1.316941
4	7.611089	15.225668	3.072803	2.000000	0.624496	31.380310	5.611084	0.001156	0.051857	1.553864
5	18.204376	36.417358	3.067404	4.000000	1.910767	34.085373	14.204346	0.002080	0.059951	1.556560
6	14.919739	29.928452	2.911185	5.000000	4.716461	17.167206	9.918457	0.013111	0.165840	1.506229
7	40.279892	80.568100	3.096311	29.000000	9.330338	34.503281	11.278809	0.007342	0.020021	1.545536
8	36.431076	73.395386	2.722670	29.000000	27.389969	21.935013	7.407471	0.036006	0.122593	1.274467
9	82.480347	166.321472	1.598897	1.000000	36.399902	45.923996	81.464355	0.019716	1.136209	1.564311
10	14.087230	28.188797	3.041603	4.000000	1.685089	28.539429	10.087158	0.003204	0.074764	1.545572
11	20.756149	41.666870	2.890079	13.000000	10.940155	16.801773	7.749512	0.025294	0.119169	1.438452
12	7.954102	15.909483	3.087484	1.000000	0.323395	56.778961	6.954102	0.000274	0.047573	1.564262
13	32.627716	65.272263	3.073669	11.000000	7.246262	30.938248	21.626709	0.007881	0.052887	1.555761
14	57.176773	114.354904	3.110479	3.000000	3.776962	73.126068	54.176758	0.000649	0.030128	1.569812
15	26.990997	54.003830	3.059772	11.000000	8.567810	23.912384	15.989014	0.012148	0.060592	1.549568
16	36.203003	77.311691	2.100856	24.000000	108.277496	16.470703	11.973877	0.112568	0.460711	0.990772
17	2.457241	5.035198	2.518267	1.000000	0.610332	10.568375	1.457031	0.013062	0.377924	1.325395
18	28.398361	57.052139	2.874341	14.000000	16.688980	19.858429	14.386475	0.028943	0.163852	1.467398
19	3.237062	6.481072	3.006891	2.000000	0.186127	37.969147	1.237061	0.000920	0.052437	1.488533
20	4.308352	8.621549	3.046536	2.000000	0.285553	34.322952	2.308350	0.000936	0.051857	1.527598
21	2.484143	5.018169	2.648895	2.000000	0.200459	27.466171	0.484131	0.003231	0.103049	1.181149
22	1.980471	3.983830	2.838953	1.000000	0.148060	28.852966	0.980469	0.001498	0.151314	1.419471
23	13.177022	26.381607	3.011832	6.000000	2.746017	19.975571	7.176758	0.006338	0.076969	1.518005
24	5.906501	11.826635	2.961140	1.000000	0.571426	26.166061	4.906494	0.001604	0.151314	1.541657
25	63.213623	127.148575	2.639084	57.000000	102.878418	27.383698	6.009766	0.080334	0.129523	1.197811
26	45.290390	90.611938	3.058171	33.000000	14.724701	32.887207	12.286621	0.012907	0.035540	1.522915
27	13.024018	26.058411	3.055106	4.000000	2.013031	23.626175	9.023926	0.003793	0.063693	1.548003
28	29.514572	60.627838	2.497097	15.000000	52.029785	15.268211	14.422119	0.079174	0.387577	1.313878
29	21.223801	42.533188	2.942909	6.000000	5.981308	21.887802	15.222412	0.011484	0.153672	1.525785
30	1.992432	3.987617	3.036511	1.000000	0.051997	78.666046	0.992432	0.000197	0.052537	1.518253
31	3.477543	6.962533	2.997240	1.000000	0.278854	28.307037	2.477539	0.001451	0.104199	1.530643
32	1.329346	2.663297	2.949425	1.000000	0.031976	84.615814	0.329346	0.000565	0.048394	1.427023
33	15.149013	30.437485	2.865583	6.000000	7.690567	14.076841	9.144531	0.024324	0.190193	1.484981
34	29.336380	59.173462	2.716838	7.000000	17.033615	20.459396	22.325195	0.027623	0.347598	1.493641

TABLE 4

STORM NO	STORMFLO	INTERFLO	RAPIDFLO	GINCH	INTERFLINCH	RAPINCH	TOTAL TIME	QFLO TO PEAK	QFLOAFTER PEAK
1	5.628342	5.607141	0.021201	0.001567	0.001562	0.000006	75.133362	3.461517	2.166824
2	10.738663	10.685075	0.053588	0.002991	0.002976	0.000015	81.719055	6.702942	4.035721
3	90.840500	77.133896	13.706604	0.025299	0.021482	0.003817	37.497070	58.618515	32.221985
4	0.624496	0.608575	0.015921	0.000174	0.000169	0.000004	7.611084	0.102419	0.522078
5	1.910767	1.847014	0.063752	0.000532	0.000514	0.000018	18.204346	0.530106	1.380661
6	4.716461	4.143235	0.573226	0.001314	0.001154	0.000160	14.918457	1.947220	2.769241
7	9.330338	9.022338	0.308000	0.002598	0.002513	0.000086	40.278809	7.540192	1.790146
8	27.389969	22.078445	5.311523	0.007628	0.006149	0.001479	36.407471	12.418488	14.971481
9	36.399902	32.919922	3.479980	0.010137	0.009168	0.000969	82.464355	1.024520	35.375381
10	1.685039	1.602720	0.082369	0.000469	0.000446	0.000023	14.087158	0.574066	1.111023
11	10.940155	9.813321	1.126834	0.003047	0.002733	0.000314	20.749512	7.123047	3.817108
12	0.323395	0.317387	0.006008	0.000090	0.000088	0.000002	7.954102	0.023643	0.299751
13	7.245262	6.767776	0.478485	0.002018	0.001885	0.000133	32.626709	2.197449	5.048813
14	3.776962	3.766152	0.010800	0.001052	0.001049	0.000003	57.176758	0.133688	3.643274
15	8.567810	8.358461	0.209349	0.002386	0.002328	0.000058	26.989014	3.808487	4.759323
16	108.277496	86.677582	21.599915	0.030153	0.024140	0.006016	35.973877	70.824631	37.452866
17	0.610332	0.377103	0.233228	0.000170	0.000105	0.000065	2.457031	0.190930	0.419401
18	16.688980	13.768891	2.920089	0.004648	0.003835	0.000813	28.386475	8.091278	8.597702
19	0.186127	0.170116	0.016010	0.000052	0.000047	0.000004	3.237061	0.103551	0.082576
20	0.285553	0.269664	0.015889	0.000080	0.000075	0.000004	4.308350	0.102419	0.183134
21	0.200459	0.155290	0.045169	0.000056	0.000043	0.000013	2.484131	0.151707	0.048752
22	0.148960	0.101863	0.046197	0.000041	0.000028	0.000013	1.980469	0.074757	0.073303
23	2.746017	2.598861	0.147157	0.000765	0.000724	0.000041	13.176758	1.172394	1.573624
24	0.571426	0.519085	0.052342	0.000159	0.000145	0.000015	5.906494	0.074757	0.496670
25	102.878418	90.216812	12.661606	0.028652	0.025125	0.003526	63.009766	91.159668	11.718750
26	14.724701	14.310994	0.413707	0.004101	0.003986	0.000115	45.286621	11.838181	2.886520
27	2.013031	1.955613	0.057418	0.000561	0.000545	0.000016	13.023926	0.467712	1.545319
28	52.033785	41.807632	10.222153	0.014490	0.011643	0.002847	29.422119	20.777908	31.251877
29	5.681308	5.307069	0.374239	0.001666	0.001478	0.000188	21.222412	2.259674	3.721634
30	0.051937	0.044921	0.007016	0.000014	0.000013	0.000002	1.992432	0.026096	0.025901
31	0.278654	0.252647	0.026207	0.000078	0.000070	0.000007	3.477539	0.051554	0.227301
32	0.031376	0.027922	0.003453	0.000009	0.000008	0.000001	1.329346	0.024048	0.007927
33	7.690567	6.719656	0.971911	0.002142	0.001871	0.000271	15.144531	3.587250	4.103317
34	17.033819	13.877348	3.156267	0.004744	0.003865	0.000879	29.325195	5.823593	11.210022

TABLE 5

SUMMARY OF STORM FLOW DATA

STORM NO	STORMFLO	%INTERFLO	%RAPIDFLO	% BEFORE PK	% AFTER PK	
1	5.628342	99.62	0.38	61.50	38.50	1
2	10.738663	99.50	0.50	62.42	37.58	2
3	90.840500	84.91	15.09	64.53	35.47	3
4	0.624496	97.45	2.55	16.40	83.60	4
5	1.910767	96.66	3.34	27.74	72.26	5
6	4.716461	87.85	12.15	41.29	58.71	6
7	8.330338	96.70	3.30	80.81	19.19	7
8	27.389969	80.61	19.39	45.34	54.66	8
9	36.399902	90.44	9.56	2.81	97.19	9
10	1.685089	95.11	4.89	34.07	65.93	10
11	10.940155	89.70	10.30	65.11	34.89	11
12	0.323395	98.14	1.86	7.31	92.69	12
13	7.246262	93.40	6.60	30.33	69.67	13
14	3.776962	99.71	0.29	3.54	96.46	14
15	8.567810	97.56	2.44	44.45	55.55	15
16	108.277496	80.05	19.95	65.41	34.59	16
17	0.610332	61.79	38.21	31.28	68.72	17
18	16.688980	82.50	17.50	48.48	51.52	18
19	0.186127	91.40	8.60	55.63	44.37	19
20	0.285553	94.44	5.56	35.87	64.13	20
21	0.200459	77.47	22.53	75.68	24.32	21
22	0.148060	68.80	31.20	50.49	49.51	22
23	2.746017	94.64	5.36	42.69	57.31	23
24	0.571426	90.84	9.16	13.08	86.92	24
25	102.878418	87.69	12.31	88.61	11.39	25
26	14.724701	97.19	2.81	80.40	19.60	26
27	2.013031	97.15	2.85	23.23	76.77	27
28	52.029785	80.35	19.65	39.93	60.07	28
29	5.981308	88.73	11.27	37.78	62.22	29
30	0.051997	86.39	13.61	50.19	49.81	30
31	0.278854	90.60	9.40	18.49	81.51	31
32	0.031976	87.32	12.68	75.21	24.79	32
33	7.690567	87.36	12.64	46.64	53.36	33
34	17.033615	81.47	18.53	34.19	65.81	34

APPENDIX 2

The Hydrograph Analysis Program Written in Fortran IV language

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FORTRAN IV G LEVEL  18                  MAIN                DATE = 71201          22/08/17

0001                  DIMENSION S(9000),HOUR(9000),QFLL(300),TS(300),TP(300),TE(300),
                     2RS(300),RE(300),DR1(300),DR2(300),DT1(300),DT2(300),RP(300),
                     3UP(300),DN(300),PERIM(300),A(300),PERFL(300),A2(300),ARISE(300),
                     4AGLDN(300),BASE(300)
0002                  DIMENSION QFLPK(300),QFPPK(300)
0003                  DIMENSION TOTTM(300),QINCH(300)
0004                  DIMENSION SUBFF(300),RFLL(300),SLBIN(300),RINCH(300)
0005                  DIMENSION PIFLO(300),PRFLO(300),PQBPK(300),PQAPK(300)
                C  THE PROGRAM ACCOMODATES 300 STORMS.  IF A LARGER NUMBER OF STORMS IS
                C  ANTICIPATED, THE DIMENSION STATEMENT ABOVE SHOULD BE CHANGED, OR
                C  THE NUMBER OF DATA BEING ANALYZED AT ONE TIME SHOULD BE REDUCED.
0006                  DO 7  J=1,9000
0007           7      S(J)=-1.0
0008                  ENDS=-1.0
                C  IN THIS PROGRAM,S=STAGE.THE CONVERSION FROM STAGE TO CFS TAKES PLACE
                C  BELOW,UNDER'Q= ', AND 'RS(K)= '.CONVERSION CONSTANTS SHOULD BE CHANGED
                C  TO FIT THE WEIR BEING USED.
0009                  READ (5,1,END=8)S
                C  THE FOLLOWING FORMAT STATEMENT MUST FIT THE FORMAT IN WHICH THE INPUT
                C  DATA FOR STAGE ARE PUNCHED.
0010           1      FORMAT (10X,12F4.3,22X)
                C  IF HYDROGRAPH READINGS ARE TAKEN AT INTERVALS OTHER THAN ONE HOUR,
                C  THEN A SEPARATE 'READ' STATEMENT SHOULD BE MADE.
0011           8      DO 2 J=1,9000
0012           2      HOUR(J)=J
0013                  J=1
0014                  K=1
0015           4      START=S(J)
0016                  IF(S(J).LE.ENDS) GO TO 8001
0017           3      IF(S(J+1).GT.START) GO TO 100
0018                  IF(S(J+1).LE.START) J=J+1
0019                  GO TO 4
0020           100    WRITE(6,5) K
0021           5      FORMAT('1',50X,'TABLE 1'/15X,'STORM NUMBER',I4)
0022                  TS(K)=HOUR(J)
0023                  Q=1.522*(8.0**0.026)
0024                  RS(K)=S(J)**Q*32.0
0025                  WRITE (6,6) TS(K),RS(K)
0026           6      FORMAT(2X,'STORM BEGINS AT',F10.2,3X,'INITIALRUNOFF RATE IS',F12.6
                     2/2X,'TIME BASEFLORATE RUNOFRATE   BASEFLO   TOTALFLO   STORMFLO%
                     3 STORMFLO   INTERFLO   RAPIDFLO INTERFLORATE')
0027                  U=0
0028                  RC=0
0029                  UCUM1=RS(K)
0030                  DELAF=0
0031                  QFLO=0
0032                  RP(K)=RS(K)
0033                  TP(K)=HOUR(J)
0034                  U2=0
0035                  SUBFL=0
0036                  RFLO=0
0037                  UCUM3=RS(K)
0038                  R1=S(J)**Q*32.0
0039                  R2=S(J+1)**Q*32.0
0040           200    DIFP=ABS(R2-UCUM1)
0041                  DIFT=HOUR(J+1)-HOUR(J)
0042                  T=HOUR(J+1)
0043                  H=SQRT(DIFP**2+DIFT**2)
0044                  IF(H.LT.DIFP)H=DIFP
0045                  IF(H.LT.DIFT)H=DIFT
0046                  RC=(R2+R1)/2.0*DIFT+RC
0047                  ALPHA=ATAN(DIFP/DIFT)
0048                  BETA=(H*ALPHA-DIFP)/H
0049                  IF(BETA.LE.0) BETA=0
0050                  CSA=1.0+SIN(ALPHA)
0051                  U=EXP(-CSA)*SQRT(DIFP*DIFT*TAN(BETA))
0052                  UCUM2=U+UCUM1
0053                  IF(R2.GT.RP(K))TP(K)=T
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FORTRAN IV G LEVEL  18                  MAIN                    DATE = 71201          22/08/17

0054                IF(R2.GT.RP(K))    RP(K)=R2
0055                IF(S(J+2).LE.ENDS) GO TO 8001
0056                R3=S(J+2)**Q*32.0
0057                DIFT2=HOUR(J+1)-HOUR(J)
0058                DIFR2=R2-UCUM3
0059                IF(DIFR2.LE.0) GAMMA=0.0
0060                IF(DIFR2.LE.0)      GO TO 15
0061                H2=SQRT(DIFR2**2+DIFT**2)
0062                GAMMA=H2/(DIFT2+3.0*DIFR2)
0063          15    U2=GAMMA*DIFR2
0064                UCUM4=UCUM3+U2
0065                IF(UCUM4.LE.UCUM2) UCUM4=UCUM2
0066                IF(UCUM4.GE.R2) UCUM4=R2
0067                IF(UCUM2-R2) 10,11,12
0068          10    DELAF=DELAF+(UCUM1+UCUM2)/2.0*DIFT
0069                PERC=100.0-DELAF*100.0/RC
0070                QFLO=RC-DELAF
0071                SUBFL=SUBFL+(UCUM3+UCUM4-UCUM1-UCUM2)/2.0*DIFT2
0072                RFLO=QFLO-SUBFL
0073                IF(T.EQ.TP(K)) QFLPK(K)=QFLO
0074                WRITE (6,13) T,  UCUM2,R2,DELAF,RC,PERC,QFLO,SUBFL,RFLO,UCUM4
0075          13    FORMAT(1X,F7.2,9F11.6)
0076                R1=R2
0077                R2=R3
0078                UCUM1=UCUM2
0079                UCUM3=UCUM4
0080                J=J+1
0081                IF(S(J).LE.ENDS) GO TO 8001
0082                GO TO 200
0083          11    DELAF=DELAF+(UCUM1+UCUM2)/2.0*DIFT
0084                PERC=100.0-DELAF*100.0/RC
0085                QFLO=RC-DELAF
0086                SUBFL=SUBFL+(UCUM3+UCUM4-UCUM1-UCUM2)/2.0*DIFT2
0087                SUBFF(K)=SUBFL
0088                RFLO=QFLO-SUBFL
0089                RFLL(K)=RFLO
0090                QFPPK(K)=QFLL(K)-QFLPK(K)
0091                WRITE (6,13) T,  UCUM2,R2,DELAF,RC,PERC,QFLO,SUBFL,RFLO,UCUM4
0092                RF(K)=R2
0093                TF(K)=T
0094                QFLL(K)=QFLO
0095                PIFLO(K)=SUBFF(K)*100.0/QFLL(K)
0096                PRFLO(K)=100.0/QFLL(K)*RFLL(K)
0097                PQPPK(K)=100.0/QFLL(K)*QFLPK(K)
0098                PQAPK(K)=100.0/QFLL(K)*QFPPK(K)
0099                K=K+1
0100                J=J+1
0101                IF(S(J).LE.ENDS)    GO TO 8001
0102                GO TO 4
0103          12    R1=(R2-R1)/DIFT
0104                R2=U/DIFT
0105                TIMEX=(-R1+UCUM1)/(R1-R2)
0106                TIMEX=HOUR(J)+TIME
0107                UCUM2=UCUM1+R2*TIME
0108                DELAF=DELAF+(UCUM1+UCUM2)/2.0*TIME
0109                XR=UCUM2
0110                RC=RC-(R2+XR)/2.0*(DIFT-TIME)
0111                PERC=100.0*(-DELAF*100.0/RC
0112                 QFLO=RC-DELAF
0113                QFLL(K)=QFLO
0114                QFPPK(K)=QFLL(K)-QFLPK(K)
0115                SUBFL=SUBFL+(UCUM3-UCUM1)/2.0*TIME
0116                SUBFF(K)=SUBFL
0117                RFLO=QFLO-SUBFL
0118                RFLL(K)=RFLO
0119                WRITE (6,13)TIMEX,  UCUM2,XR,DELAF,RC,PERC,QFLO,SUBFL,RFLO,UCUM2
0120                RF(K)=XR
0121                TF(K)=TIMEX
```

```
0122              PIFLO(K)=SUBFF(K)*100.0/QFLL(K)
0123              PRFLO(K)=100.0/QFLL(K)*RFLL(K)
0124              PQBPK(K)=100.0/QFLL(K)*QFLPK(K)
0125              PQAPK(K)=100.0/QFLL(K)*QFPPK(K)
0126              J=J+1
0127              K=K+1
0128              IF(S(J).LE.ENDS)   GO TO 8001
0129              GO TO 4
0130         8001 WRITE(6,8110)
0131         8110 FORMAT('1',50X,'TABLE 2')
0132              WRITE(6,8003)
0133         8003     FORMAT(20X,'SUMMARY OF STORM DATA'/1X,' NO  TIME START TIME PE
                2AK TIMEEND  R START    R PEAK    R END   STORMFLO   INTERFLO    RA
                3PIDFLO')
0134              II=K-1
0135              DO 8100 J=1,II
0136              WRITE(6,8008)     J,TS(J),TP(J),TE(J),RS(J),RP(J),RE(J),QFLL(J),
                2SUBFF(J),RFLL(J)
0137         8008 FORMAT(1X,I3,9F10.4)
0138         8100 CONTINUE
0139              WRITE(6,8002)
0140         8002 FORMAT('1',50X,'TABLE3'/1X,'STORM',2X,'STORMFLO',29X,'TIME',18X,'P
                2ERIMETER/',4X,'RECESSION',' BASE LINE',3X,'RISING',3X,'FALLING'/1X
                3,'NO',3X,'BASE LINE',3X,'PERIMETER',4X,'TOP ANGLE',3X,'TO PEAK',5X
                4,'STORMFLO',2X,'LN(1+STORMFLO)',4X,'TIME',7X,'ANGLE',3X,'LIMB ANGL
                5E',1X,'LIMB ANGLE')
0141              DO 8200 J=1,II
0142              DR1(J)=RP(J)-RS(J)
0143              DR2(J)=RP(J)-RE(J)
0144              DT1(J)=TP(J)-TS(J)
0145              DT2(J)=TE(J)-TP(J)
0146              UP(J)=SQRT(DR1(J)**2+DT1(J)**2)
0147              DN(J)=SQRT(DR2(J)**2+DT2(J)**2)
0148              BASE(J)=SQRT((RE(J)-RS(J))**2+(TE(J)-TS(J))**2)
0149              PERIM(J)=UP(J)+DN(J)+BASE(J)
0150              A(J)=ATAN(DT1(J)/DR1(J))+ATAN(DT2(J)/DR2(J))
0151              A2(J)=ATAN((RE(J)-RS(J))/(TE(J)-TS(J)))
0152              ARISE(J)=ATAN(DR1(J)/DT1(J))
0153              AGLDN(J)=ATAN(DT2(J)/DR2(J))
0154              PERFL(J)=PERIM(J)/ALOG((QFLL(J)+1.0))
0155              TOTTM(J)=TE(J)-TS(J)
0156              WRITE(6,8009)     J,BASE(J),PERIM(J),A(J),DT1(J),QFLL(J),PERFL(J),
                2  DT2(J),A2(J),ARISE(J),AGLDN(J)
0157         8009 FORMAT(1X,I3,2X,8F12.6,2F9.6)
0158         8200 CONTINUE
0159              WRITE(6,8120)
0160         8120 FORMAT('1',50X,'TABLE 4')
0161              WRITE (6,8703)
0162         8703     FORMAT( 1X,'STORM NO   STORMFLO    INTERFLO    RAPIDFLO   QINC
                2H    INTERFLINCH    RAPINCH   TOTAL TIME  QFLO TO PEAK QFLOAFTER P
                3EAK')
             C   AINCH IS A CONSTANT FOR CONVERTING CFS INTO INCHES
0163              AINCH=3600.0*640.0*12.0/(5280.0**2)
             C   ACREK IS THE AREA OF THE WATERSHED BEING STUDIED IN ACRES
             C   THE VALUE OF 'ACREK' MUST BE CHANGED TO FIT THE WATERSHED
             C   BEING STUDIED.
0164              ACREK=3561.0
0165              DO 8720 J=1,II
0166              QINCH(J)=QFLL(J)*AINCH/ACREK
0167              SUBIN(J)=SUBFF(J)*AINCH/ACREK
0168              RINCH(J)=RFLL(J)*AINCH/ACREK
0169              WRITE (6,8700) J,QFLL(J),SUBFF(J),RFLL(J),QINCH(J),SUBIN(J),
                2RINCH(J),TOTTM(J),QFLPK(J),QFPPK(J)
0170         8700 FORMAT(1X,I3,5X,9F12.6)
0171         8720 CONTINUE
0172              DO 8600 J=1,II
```

```
FORTRAN IV G LEVEL  18                  MAIN                    DATE = 71201          22/08/17

0173          8600 WRITE (7,8000) A2(J),ARISE(J),A(J),AGLDN(J),DT1(J),DT2(J),TOTTM(J)
                  2,DR1(J),DR2(J),QFLL(J),PERIM(J),PERFL(J),QINCH(J),TS(J),TE(J),
                  3RP(J),QFLPK(J),QSRPK(J),SUBEF(J),RFLL(J)
0174          8000 FORMAT(5E15.6/5E15.6/3E15.6,2F7.2/5E12.6,17X,'401')
0175               WRITE (6,8130)
0176          8130 FORMAT ('1',50X,'TABLE 5')
0177               WRITE(6,7001)
0178          7001     FORMAT(10X,'SUMMARY OF STORM FLOW DATA'/1X,'STORM NO',2X,'STORM
                  2FLD       %INTERFLD      %RAPIDFLD      % BEFORE PK   % AFTER PK')
0179               DO 7002 J=1,11
0180          7002 WRITE(6,7003) J,QFLL(J),PIFLC(J),PRFLC(J),PQRPK(J),PQAPK(J),J
0181          7003 FORMAT(1X,I3,5X,F13.6,4F13.2,I4)
0182          9999 STOP
0183               END
```

BETHLAHMY, NEDAVIA

1972. Hydrograph analysis: a computerized separation technique. USDA Forest Serv. Res. Pap. INT-122, 19 p., illus.

Describes a computer program (Fortran IV language) designed to analyze hydrographs. Using only input data of stage and time, the program automatically determines the beginning and end of each event, analyzes each event with respect to all its hydrologic characteristics (including a partitioning of base flow, interflow, and rapid flow), and then prints a detailed analysis of each event and a series of summaries of all events analyzed.

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EFFECT OF LOGGING ROADS ON SEDIMENT PRODUCTION RATES IN THE IDAHO BATHOLITH

Walter F. Megahan and Walter J. Kidd

AUG 24 S. L. TECH. & AGR. DIV.

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INTERMOUNTAIN FOREST AND RANGE
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Cover Photo:--Typical midelevation stream-cut topography in the Idaho Batholith.

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ABSTRACT

Effects of logging road construction on sediment production rates were studied on small, ephemeral drainages in the Idaho Batholith, a large area of granitic rock characterized by steep slopes and highly erodible soils. For the 6-year study period, about 30 percent of the total accelerated sediment production from roads was caused by surface erosion; the remainder resulted from mass erosion. Surface erosion on roads decreased rapidly with time after extremely high initial rates. A mass failure of a road fill slope occurred about 4 years after construction, when surface erosion had fallen to a low rate. The sediment production rate attributed to erosion within the area disturbed by road construction averaged 770 times greater (220 because of surface erosion and 550 because of mass erosion) than that for similar, undisturbed lands in the vicinity.

Results suggest three guides to use in the control of surface erosion on roads and subsequent downslope sediment movement in the Idaho Batholith: (a) Apply erosion control measures immediately after road construction for maximum effectiveness; (b) ensure that treatments protect the soil surface until vegetation becomes established; (c) take advantage of downslope barriers (logs, branches, etc.) to effectively delay and reduce the downslope movement of sediment.

INTRODUCTION

There is considerable evidence that logging roads are the primary source of accelerated erosion and sedimentation on logged watersheds. Packer (1967) concluded:

> Of man's activities that disturb vegetation and soil in forests, none are greater precursors of sediment damage to water quality than the construction of roads.

Numerous others have substantiated Packer's conclusion (Anderson 1954; Reinhart and others 1963; Haupt and Kidd 1965; and Leaf 1966).

Logging road construction is particularly damaging in highly erodible areas, such as the 16,000-square-mile Idaho Batholith (fig. 1), which is characterized by steep topography and shallow, coarse-textured soils overlying granitic bedrock. Soils derived from parent material of this type were the most erodible to be found in Oregon and northern California (Anderson 1954; and André and Anderson 1961). Recognition of such unstable soil conditions on steep batholith lands led to the initiation of the Zena Creek logging study in 1959 (Craddock 1967). The study, which was a cooperative effort carried out by the Intermountain Region and the Intermountain Station of the USDA Forest Service, was conducted near the confluence of the South Fork of the Salmon and the Secesh Rivers in the mountains of central Idaho.

Part of the research effort included a study to evaluate the effects of jammer and skyline logging systems on erosion and sedimentation in the Deep Creek drainage (Megahan and Kidd In press). The purpose of this report is to explore types and rates of change of the road erosion that occurred during the Deep Creek study.

Figure 1.--Location map of the Idaho Batholith and the study area.

STUDY AREA AND METHODS

The study area is within the confines of the Zena Creek logging study area near the head of the Deep Creek drainage, a tributary to the Secesh River. Three contiguous, ephemeral drainages comprise the 10-acre area (fig. 2). Annual precipitation at the study area averages 28.3 inches, of which about 60 percent occurs as snow.

The dominant tree species are ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco). The coarse, loamy sand soils are derived from quartz monzonite bedrock and are poorly developed, exhibiting only A and C horizons. Additional descriptive data are summarized in table 1.

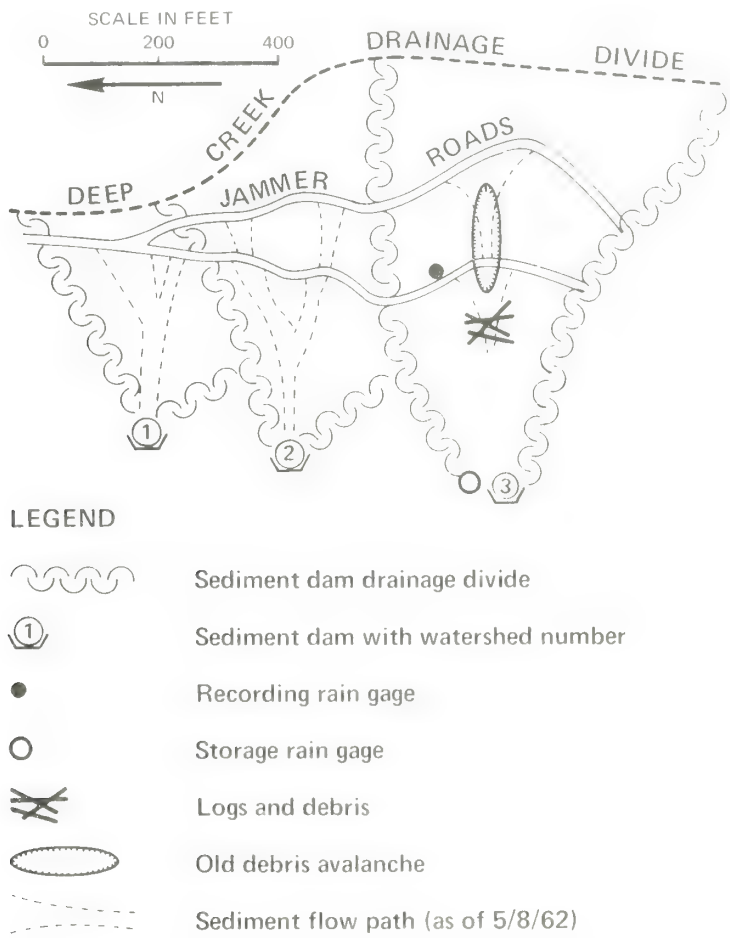

Figure 2.--Schematic map of the study watersheds.

Table 1.--*Descriptive data for watersheds in the Deep Creek study area*

Characteristic	Watershed No. 1	2	3
Mean side slope gradient (percent)	74	65	71
Channel gradient (percent)	70	63	61
Watershed aspect (degrees azimuth)	274	285	270
Mean soil depth (inches)	16	22	22

Sediment movement in the study area is almost exclusively bedload because of the extremely coarse texture of the soil and parent materials; consequently, small dams were used to obtain sediment yields. Data from the sediment dams were collected twice a year--following the snowmelt period (about June 1); and near the end of the water year (about September 30). Accumulations of sediment behind dams were surveyed, using a grid of closely spaced cross sections, beginning on November 1, 1960.

Jammer roads totaling about 0.36 mile in length were built on the three watersheds during October 1961; standard sidecast construction practices were used (table 2). From October 25, 1962, to November 14, 1962, approximately 80 percent of the commercial timber was removed from the study area. Standard postlogging erosion control measures, including water bars and grass seeding, were installed on the jammer roads. Postlogging measurements of sediment production were continued on schedule until September 21, 1967.

Table 2.--*Jammer road construction on the study watersheds*

Watershed No.	Road length	Area disturbed: Road tread	Fill slope	Cut slope	Total	Watershed area	Percent watershed disturbed
	Feet	*Acres*					*Percent*
1	420	0.21	0.07	0.15	0.43	1.80	24
2	568	.28	.22	.14	.64	3.50	18
3	904	.38	.39	.25	1.02	4.70	22
Total	1,892	.87	.68	.54	2.09	10.00	21

RESULTS

The amount of sediment accumulated in the dams that could be attributed solely to road erosion was determined by comparing data on the three watersheds to data of the same type collected on five contiguous and similar but unroaded watersheds (Megahan and Kidd In press). Sediment yield data for individual watersheds shown in table 3 represent material eroded from the road prism by surface erosion unless otherwise noted. Surface erosion can be described as movement of individual soil particles; it includes both sheet and gully erosion.

Table 3.--*Sediment yields from road erosion in the Deep Creek study area*

Measurement period	Elapsed time	Watershed 1	Watershed 2	Watershed 3	Total	Average
	Days	*Cubic feet*				*Tons/day/mi. of road*
11/60 - 6/61	232	0.0	0.0	0.0	0.0	0.0
6/61 - 11/61	134	.0	.0	.0	.0	.0
11/61 - 6/62[1]	238	778.3	1,089.0	14.7	1,882.0	109.0
6/62 - 10/62	120	67.6	62.8	9.1	139.5	16.0
10/62 - 11/62	20	--	Period of logging on study watersheds			--
11/62 - 5/63	195	.0	83.3	68.3	151.6	10.7
5/63 - 9/63	113	.0	73.0	.0	73.0	7.8
9/63 - 5/64	251	.0	1.8	9.7	11.5	.6
5/64 - 10/64	128	.0	.0	.0	.0	.0
10/64 - 6/65[2]	252	.0	40.4	--	40.4	4.4
6/65 - 9/65	105	.0	9.4	--	9.4	2.7
9/65 - 6/66	258	2.2	60.4	--	62.6	6.5
6/66 - 9/66	100	.0	.0	--	.0	.0
9/66 - 5/67	250	.0	11.3	--	11.3	1.2
5/67 - 9/67	120	.2	32.0	--	32.2	7.3

Total sediment accumulation from surface erosion =	2,413.5 cubic feet
Total sediment accumulation from mass erosion[2] =	6,030.0 cubic feet
Total sediment accumulation from road erosion =	8,443.5 cubic feet

[1]Road construction completed during this period.
[2]Dam number 3 irreparably destroyed by a road fill failure (mass erosion) on 4/23/65. Field measurements at the failure site indicated 6,030 cubic feet of material moved down the channel.

Figure 3.--Downslope sediment movement resulting from road erosion above. Sediment is easily traced because of the light color, coarse texture, and uniform gradation of the materials.

Sediment production during the first time period after construction was extremely high on Watersheds 1 and 2 but decreased rapidly in subsequent periods. However, this didn't occur on Watershed 3. A survey of sediment flow was conducted May 8, 1962, to examine this anomalous behavior on Watershed 3. The downslope movement of sediment on each watershed was mapped from its source to its downslope terminus. This is easily done because of the light color, the coarse texture, and the uniform gradation of the eroded material in this area (fig. 3). The cause of the limited sediment production on Watershed 3 was readily apparent; a barrier of logs and debris in the drainage bottom was catching the material en route (fig. 2).

Sediment flow phenomena have been noted elsewhere and research has shown that natural and/or artificial barriers delay and reduce coarse sediment movement downslope (Trimble and Sartz 1957; Haupt 1959; Packer and Christensen 1964).

Additional erratic behavior was noted on Watershed 3. A natural landslide scarp existed on this watershed prior to road construction. This type of slide, classified as a debris avalanche (National Research Council, Highway Research Board 1958), is characterized by rapid downslope movement of soil and rock material having varying

Figure 4.--View of the lower jammer road in Watershed 3, where the debris avalanche originated because of a road fill failure.

Figure 5.--The debris avalanche scoured the [illegible] to bedrock. The slide obliterated the sediment dam (formerly in the channel bottom) and splashed mud on top of the storage rain gage tower (see arrow).

water contents. Debris avalanches usually leave a discernible elongated scar to bedrock at the slide origin and often exhibit a characteristic downslope slide path. The lower jammer road in Watershed 3 was constructed through the old slide area without taking special precautions (fig. 2). In April 1965, a combination of rainfall and snowmelt generated a massive failure of the road fill material at the site of the old landslide (fig. 4). The slide scoured the entire length of the channel to bedrock in Watershed 3 and destroyed the sediment dam (fig. 5). Postslide measurements indicated that approximately 6,030 cubic feet of sediment moved down the channel.

Total Erosion

The total surface erosion for the three watersheds for each sampling period is shown in table 3. Data for all three watersheds (before sediment dam 3 was destroyed) are included in this total because natural sediment barriers are commonly found on slopes in this vicinity. Surface erosion for the entire 6-year study period totaled 2,413.5 cubic feet. The 1965 mass erosion event amounted to an additional 6,030 cubic feet of sediment, which, added to the surface erosion, totaled 8,443.5 cubic feet of erosion from roads for the 6-year study period. Thus, about 30 percent of the soil loss could be attributed to surface erosion and the remainder to mass erosion. Actually, the total percentage of surface erosion might be greater by a few percent because some erosion undoubtedly continued in Watershed 3 after the destruction of the sediment dam.

The effects of road construction and logging on sediment movement can best be appreciated by comparing the rates generated by these uses to the rates for undisturbed lands. Sediment dams were used to determine sediment yields on undisturbed, perennial watersheds in the immediate vicinity. These included the Oompaul, Hamilton, Tailholt, and Circle End drainages, which are 740, 460, 1,625, and 930 acres in size, respectively.

During the 6-year study period, sediment data were collected on one or more of these watersheds and included the effects of natural landslides within the drainages. For the study period, the average sedimentation rate on the undisturbed watersheds (weighted for drainage area) was 0.07 ton/mi.^{2}/day. This rate is not unreasonable for undisturbed forested lands in the Rocky Mountains; for example, Leaf (1966) reports average sediment production of 0.02 ton/mi.^{2}/day for watersheds in Colorado.

Using this average sediment production rate of 0.07 ton/mi.^{2}/day for undisturbed lands, we calculated that about 10.9 cubic feet of sediment would have been collected in the three sediment dams from the area disturbed by roads during the 6-year study period if the roads hadn't been built. Comparing this to actual sediment production from road erosion for the 6-year study period, we find that sediment yields increased approximately 770 times following road construction (220 times because of accelerated surface erosion *plus* 550 times because of accelerated mass erosion)!

Time Trends in Surface Erosion

The average annual sediment production from surface erosion on roads is an informative way of evaluating time trends (table 4). Note that about 84 percent of the total sediment for the 6-year study period was produced during the first year after construction. By the end of the second year, the total sediment production had risen to over 93 percent.

A histogram of the average sediment production data for individual measurement periods is an even more enlightening way of evaluating time trends (fig. 6). A second y axis on the right side of the figure indicates how many times sediment production from roads exceeds that from similar lands that are undisturbed. Note that sediment production during the first time period after construction averaged 109 tons per day per square mile of road--about 1,560 times greater than sediment production from similar lands that are undisturbed. Note also that this high initial rate decreases rapidly during subsequent measurement periods. As noted previously, sediment production rates resulting from surface erosion averaged about 220 times greater than the rates for undisturbed lands during the 6-year study period.

Table 4.--*Sediment production due to surface erosion on roads by years after construction*

Year	Sediment production	Percent of total	Accumulated percent
	Cubic feet		
1961-62	2,021.5	83.8	83.8
1962-63	226.6	9.4	93.2
1963-64	14.3	0.6	93.8
1964-65	54.2	2.2	96.0
1965-66	55.4	2.3	98.3
1966-67	41.5	1.7	100.0
Total	2,413.5	100.0	

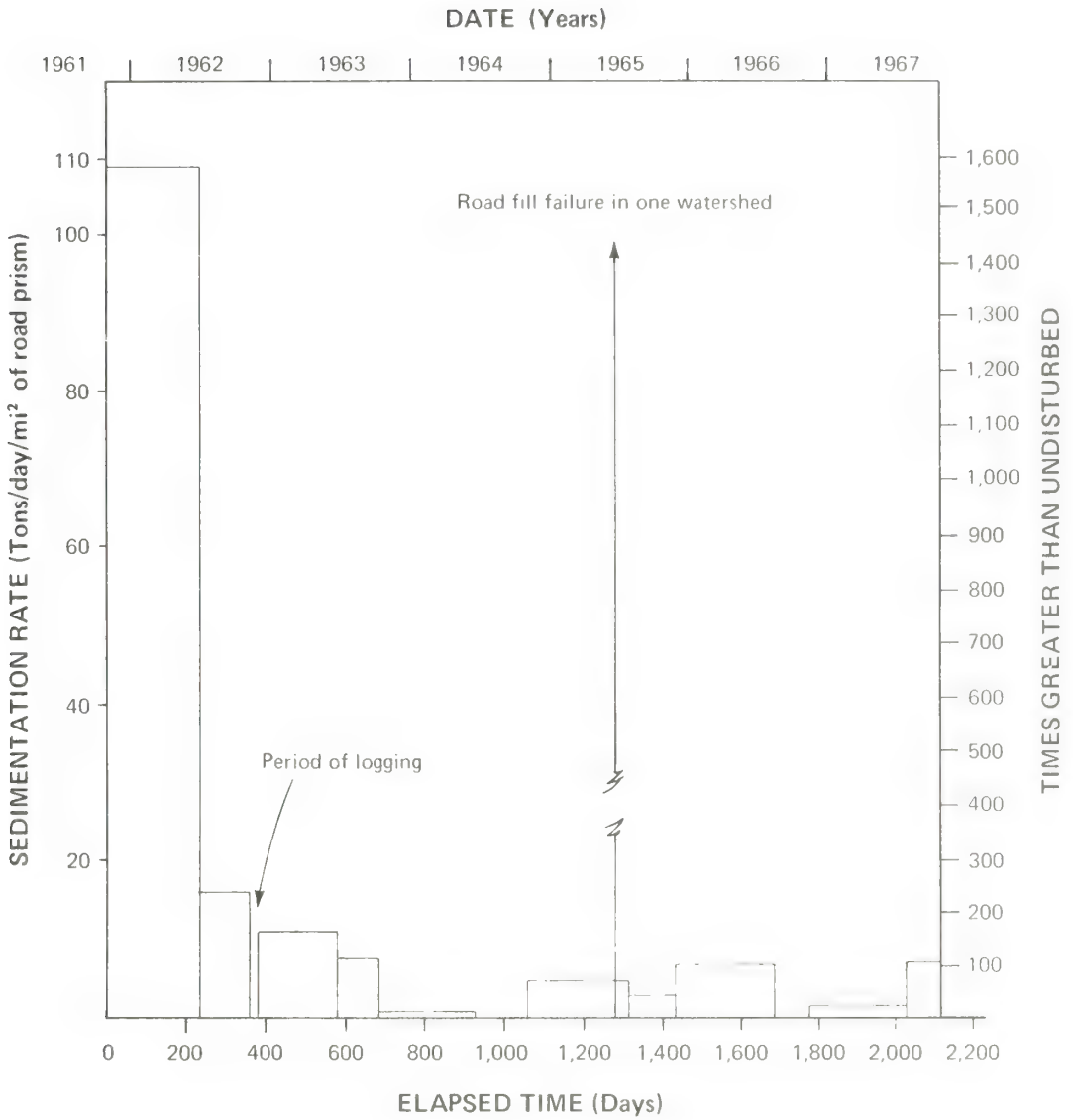

Figure 6.--Sediment production over time from surface erosion on jammer roads.

Intuitively, one can visualize how bare, unprotected material in a road prism could be subject to extremely high surface erosion immediately after construction. However, in time, the more erodible materials are removed and vegetation and litter begin to accumulate; this causes a decrease in surface erosion rates. Research data elsewhere suggest time trends in sediment production from road erosion (Rice and Wallis 1962; Reinhart and others 1963; Haupt and Kidd 1965; Vice and others 1969; Fredriksen 1970). In our study, sediment production rates had decreased progressively to zero prior to the 1964-65 measurement period. In subsequent measurement periods these ratios exhibited considerable fluctuations; ranging from zero to about 100 times greater in roaded areas than on undisturbed lands (fig. 6). Recent studies (Anderson

Figure 7.--Granitic rocks in the Idaho Batholith exhibit various degrees of weathering. Road cuts in the more highly weathered types continue to supply sediment for years.

1970) indicate that sediment production increases greatly after a major storm event such as occurred in December 1964 in California. The same storm hit Deep Creek and, coupled with the April 1965 event, apparently caused the increases found in Deep Creek. Anderson reports that high poststorm sedimentation tends to decrease with time; however, this trend was not detected in Deep Creek for the measurement periods following the April 1965 storm.

Actually it is doubtful that erosion on roads in the Idaho Batholith will permanently decrease within a reasonable time to the level that existed before disturbance. The road tread and steep cut slopes in the Deep Creek area are composed of weathered granitic bedrock that continues to disintegrate after exposure faster than natural stabilization can take place (fig. 7). The material resulting from bedrock disintegration is readily transported during subsequent runoff events. Similar bedrock conditions are found throughout much of the unglaciated portions of the Idaho Batholith.

DISCUSSION AND CONCLUSIONS

Total sediment production per unit area of road prism increased an average of 770 times for the 6-year study period. At present, the impact such an increase will have on the important downstream salmon spawning resources is undefined; however, there are indications that this level of impact is intolerable (Richards 1963). Short of forbidding all road construction, our findings emphasize the need for: (a) More careful planning to minimize the mileage of road construction, including consideration of logging systems that require fewer roads; and (b) diligent location, design, construction, and maintenance to minimize erosion on the roads that are built.

Surface erosion following road construction on steep, highly erodible batholith lands, such as those found in Deep Creek, decreases rapidly with time. About 85 percent of the erosion occurs during the first year after construction. This emphasizes that (a) measures to control surface erosion must be applied as soon after construction as possible to be effective; and (b) reseeding alone, as was carried out on Deep Creek, is not the complete answer because vegetation is slow to respond.

Observations suggest that most of the high initial surface erosion is actually the result of erosion on exposed road fills (fig. 8). Considerable data indicate that erosion on granitic road fills can be greatly reduced by stabilization measures such as the treatments listed in table 5. Note that erosion rates on granitic road fills can be reduced up to 99 percent by such stabilization treatments. The largest proportion of surface erosion occurs during the first year and is generally the result of erosion on fill slopes; therefore, it appears to be possible to greatly reduce sedimentation caused by surface erosion on roads using these fill slope stabilization treatments.

After about 3 years, the extremely high initial sediment yields in Deep Creek had dropped dramatically but still averaged about 50 times greater than did sediment production on undisturbed lands. The erosion control treatments on road fills listed in table 5 and water control measures on the road tread (e.g., culverts, etc.) should help to reduce high, long-term sedimentation rates. However, it is not likely that sediment yields will drop to the levels expected on undisturbed lands because the cut slopes remain active sediment sources and, at present, practical erosion control measures are not feasible.

Even though erosion is occurring within a road prism it need not necessarily increase sediment yields at some downstream point. Results of this study reinforce those of earlier studies that showed the effectiveness of barriers (e.g., down logs, branches, etc.) in inhibiting the downslope movement of coarse granitic sediments.

Major impacts can still occur from mass erosion after sedimentation from surface erosion has dropped to a low level and (for all practical purposes) a road is considered relatively stable. In Deep Creek, a single storm event resulted in a road fill failure that accounted for about 70 percent of the total sediment production for

Figure 8.--Surface erosion on road fills constructed from granitic materials 1 year after construction.

the entire 6-year study period. Fredriksen (1970) reported similar slides on roads in steep, unstable terrain in western Oregon. Major failures of this type are not related to surface erosion rates, but rather tend to occur during large climatic events on those areas where the potential exists.

As with surface erosion, much mass erosion of road fills can be avoided by careful location, design, construction, and maintenance measures. Gonsior and Gardner (1971) listed guidelines for this purpose based on studies of slope failures in the vicinity of the Zena Creek logging study.

Table 5.--*Erosion control on road fills in the Idaho Batholith*

Stabilization measures[1]	Road location	Percent change in erosion[2]	References
None (except seed + fertilizer)	Bogus Basin	+15	Bethlahmy and Kidd 1966[3]
Planted ponderosa pine	Deadwood River	-47	Unpublished data[4]
Wood-chip mulch	Bogus Basin	-61	Bethlahmy & Kidd 1966
Straw mulch	Zena Creek	-72	Ohlander 1964
Jute netting	Zena Creek	-93	Ohlander 1964
Asphalt - straw mulch	Zena Creek	-97	Ohlander 1964
Straw mulch + netting + planted ponderosa pine	Deadwood River	-98	Unpublished data[4]
Straw mulch + netting	Bogus Basin	-99	Bethlahmy and Kidd 1966

[1]All measures except trees include items shown + grass seed and fertilizers.

[2]As compared to untreated control plots.

[3]Erosion was increased by 15 percent, possibly by the method of applying seed and fertilizer.

[4]On file at the Station's Forestry Sciences Laboratory in Boise, Idaho.

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Results suggest three guides to use in the control of surface erosion on roads and subsequent downslope sediment movement in the Idaho Batholith: (a) Apply erosion control measures immediately after road construction for maximum effectiveness; (b) ensure that treatments protect the soil surface until vegetation becomes established; (c) take advantage of downslope barriers (logs, branches, etc.) to effectively delay and reduce the downslope movement of sediment.

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PLANT DEVELOPMENT AND YIELD ON MOUNTAIN GRASSLANDS IN SOUTHWESTERN MONTANA

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

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ABSTRACT

Plant development and herbage yields were observed for 5 consecutive years on natural mountain grasslands in southwestern Montana. Data were obtained from southwest and northeast exposures at elevations of 7,100 and 8,200 ft. Differences in development and production are compared between years, exposures, elevations, and species.

Beginning of growth in any 1 year differed between species and spread over about 3 weeks at the lower elevation and 2 weeks at the upper elevation. Lomatium was one of the earliest species to begin growth and Lupinus among the latest. Maximum difference in beginning of growth over the 5 years varied from as much as 32 days for Lomatium to as few as 13 days for Lupinus; the average for all species was 20 days. Again, depending upon the particular species, growth usually began 3 to 12 days later on northeast exposures than on southwest exposures and an average delay of about 1 week was observed for all species. Start of growth was usually 19 to 37 days later at the 8,200-ft. elevation than at 7,100 ft. and averaged 27 days later for all species.

The onset of flowering of different species in any 1 year was spread over about 10 weeks at the 7,100-ft. elevation and 7 weeks at the 8,200-ft. elevation. The greatest difference

between years in onset of flowering was 22 days for early-blooming species and only 12 days for late-blooming species. Onset of flowering was generally about 1 week later on northeast than on southwest exposures and about 20 days later at 8,200 ft. than at 7,100 ft., although flowering time varies considerably between species.

The average time between cessation of flowering and start of seed dissemination was as short as 5 days for Delphinium and more than 40 days for Anemone, Besseya, and Fritillaria. Early-blooming species averaged 36 days and late-blooming species only 17 days. Generally, the grasses began seed dissemination between 18 and 20 days following flowering.

Drying times differed greatly between species. Generally, those that bloomed early dried earlier than those that bloomed later, but there were exceptions. The maximum difference between years in drying dates ranged from 19 days for the early-blooming forbs to 39 days for the grasses.

Average duration of the growth period at the 7,100-ft. elevation ranged from 62 days for Dodecatheon to 147 days for Danthonia. Differences between years in the duration of the growth period were as great as 28 days for the combined forbs and 43 days for the combined grasses. The average duration of the growth period for species common to both elevations was 103 days at 7,100 ft. and 94 days at 8,200 ft.

Herbage production on southwest exposures was generally less than that on northeast exposures, averaging 58 percent of that on the northeast exposure at the 7,100-ft. elevation and 90 percent at 8,200 ft. The relative proportions of graminoid to forb production was inconsistent between both exposures and elevations.

Yearly variations in herbage production were almost twice as great on northeast as they were on southwest exposures. Production of forbs varied more than that of graminoids. Relative variations in production for individual species were usually greater than for vegetation classes and totals.

A positive correlation existed betwen May precipitation and herbage production. A negative correlation existed between maximum temperatures of the shaded soil surface in June and July and herbage production. A multiple regression equation, utilizing a combination of five weather measurements, was developed that predicts total herbage production with an R^2 of 0.86. Similar equations, utilizing different combinations of weather measurements, were developed that predict total yield of forbs having an R^2 of 0.74 and total yield of graminoids having an R^2 of 0.52.

INTRODUCTION

Annual differences in plant growth and production are among the most commonly observed phenomena on our native rangelands. In addition, knowledge of growth and production are fundamental to understanding the dynamics of the grassland ecosystem. Despite their conspicuousness and importance, these phenomena have not been documented for all range types. Mountain grasslands of western Montana are among those areas where information is generally lacking on yearly variations in plant development and herbage yield.

During a continuing study of the relation between plant growth and weather, I accumulated data on variations in development and yield at four different mountain grassland sites. A summary of these data is presented here for those interested in mountain grassland vegetation. Resource managers should find this summary useful for judging the amount of year-to-year variability in range readiness for grazing and the variability in grazing capacity that can be expected to occur naturally on such areas.

SETTING

The four study areas selected were near the north end of the Gravelly Range in southwestern Montana, approximately 12 miles southeast of Virginia City. The areas were on gentle southwest and northeast exposures, two at an elevation of 7,100 feet and two at 8,200 feet. The two lower areas were within 200 yards of each other, whereas the higher areas, which were 5 miles away, were within 700 yards of each other. This arrangement permitted determination of differences in development and production between extreme exposures and between elevations.

The soils, derived principally from limestone, were generally deeper at the upper elevation and on northeast exposures. Annual precipitation usually ranged between 20 and 30 inches; about half fell from May through October. Precipitation during May and June was usually heavy; it accounted for about one-fourth of the yearly total.

All four areas were natural mountain grasslands dominated by *Festuca idahoensis*. Forbs were abundant. Many graminoid and forb species were common to all four areas, but other species were restricted to specific sites.

I collected data on plant development and herbage yields on all study sites for 5 consecutive years, 1964-1968. Each area was adjacent to a weather station established to measure the climate on mountain grasslands. I recently described weather variations over the same 5-year period (Mueggler 1971).

PROCEDURE

Seasonal development was recorded for plant species common to all four areas and for conspicuous species on each area. Individual plants of selected species were marked for repeated observation. Exclosures protected these plants from livestock. Dates of various developmental stages for each species were established from the development of marked plants plus supplemental observation of the surrounding plants. If development of a marked plant appeared to be abnormal, a more typical specimen was selected for subsequent observations. The areas were visited weekly from the onset of active growth in the spring until the majority of the species became dormant in the fall.

The developmental stages discussed in this report are as follows:

Forbs

1. Growth starts--first evidence of current year's herbaceous growth.
2. First bloom--first fully developed blossoms.
3. Full bloom--aspect of most individuals of the species in full flower.
4. Bloom over--approximately 90 percent of flowering completed.
5. Dissemination starts--first evidence of seed drop.
6. Plant dried--at least 90 percent of the herbage dried.

Grasses

1. Growth starts--first evidence of current year's herbaceous growth.
2. Flower stalks appear--first evidence of booted flowering culms.
3. Flowers in bloom--approximately 25 percent or more of flowers in anthesis.
4. Dissemination starts--first evidence of seed drop.
5. Drying--at least 10 percent of herbage dried.
6. Plant dried--at least 90 percent of the herbage dried.

Herbage production was measured on each area from 50 permanent 4.8-ft.^{2} plots. These plots were distributed in a series of 10 sets, five plots per set, over a relatively uniform portion of the grassland. Production was measured each year when the vegetation appeared to have reached full growth and just before many species began to dry. Generally, production data were taken between the middle and end of July at the lower elevation and about 3 weeks later at the upper elevation.

Production was determined by combining percent-weight estimates and clipping. This technique is similar, but not identical, to that proposed by Hutchings and Schmautz (1969); it is based on the concept that it is more efficient to estimate yields as a percent of total yield rather than directly as weight units. Each year, one plot in each set of five was protected from livestock grazing by a wire cage. This plot was considered the reference plot for that particular year. The reference plot was changed each year; thus, a plot served as a reference only once in 5 years. Total herbage production on each of the remaining four plots in the set was estimated as a percent of the total production on the set's reference plot. These estimates were adjusted to compensate for current livestock utilization, which usually was minor. The weight of each species on a plot was then estimated as a percent of the total production on the plot; these estimates were also adjusted to compensate for utilization. The vegetation on the reference plot was then clipped to ground level. Individual production of four selected species served as a continual check on the accuracy of the percent-weight estimates. The total production on the reference plot was used as a basis for estimating production on other plots in the set. Then, the green weight of individual species on each plot was computed. Later, the clipped material was dried to obtain the percent dry matter by important species. All production estimates were converted to dry weights expressed in pounds per acre of air-dry material.

PLANT DEVELOPMENT

The average dates of various developmental stages for 23 forbs and five grasses growing on the southwest exposure at 7,100 ft. elevation are shown in figures 1 and 2. The beginning of annual herbaceous growth for the 23 forbs spread over more than 3 weeks. *Lomatium* generally was the first plant to begin growth (April 27) and *Lupinus* the last (May 22). Usually, all five of the grasses studied began to grow during the first week in May.

The greatest difference between years for the beginning of growth was as much as 32 days for *Linum* and as few as 13 days for *Lupinus* (table 1). For most species this difference was from 16 to 24 days, and averaged 20 days (tables 1 and 2). In other words, the general start of plant growth varied approximately 3 weeks in just one 5-year period. A much greater yearly variation (45 days for grasses and 50 days for forbs) was recorded by Costello and Price (1939) over a 10-year period on mountain herblands in Utah.

The onset of flowering of the 23 forbs spread over more than 10 weeks (fig. 1). These forbs can be categorized according to when they reach full bloom as early, middle, or late season bloomers. The early bloomers are the first six species that generally reach full bloom sometime in May. The next six species, the middle season bloomers, reach full bloom in June, and the remaining species, the late season bloomers, usually do not reach full flower until sometime in July. The flowers of *Lomatium*, *Anemone*, *Besseya*, and *Fritillaria* are among the first signs that spring has finally arrived on these mountain grasslands, while the flowers of *Achillea*, *Gaillardia*, and *Campanula* are a warning that the annual floral display will soon end. The grasses ordinarily flower in mid-July; approximately 1 week elapses between the onset of flowering in the earliest, *Danthonia*, and the latest, *Agropyron* (fig. 2).

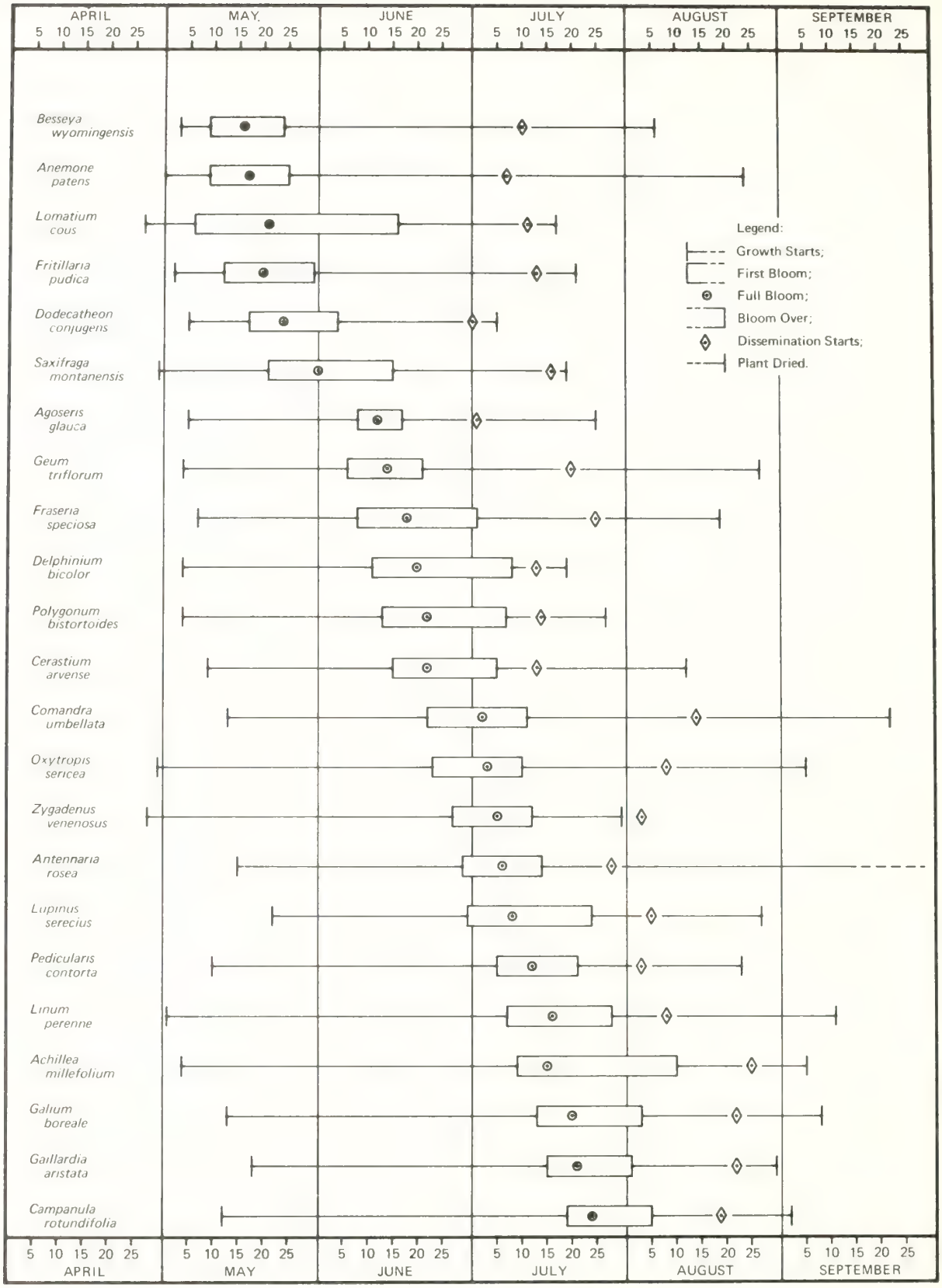

Figure 1.--The 5-year mean of developmental events for forbs on a southwest exposure at 7,100 ft.-elevation.

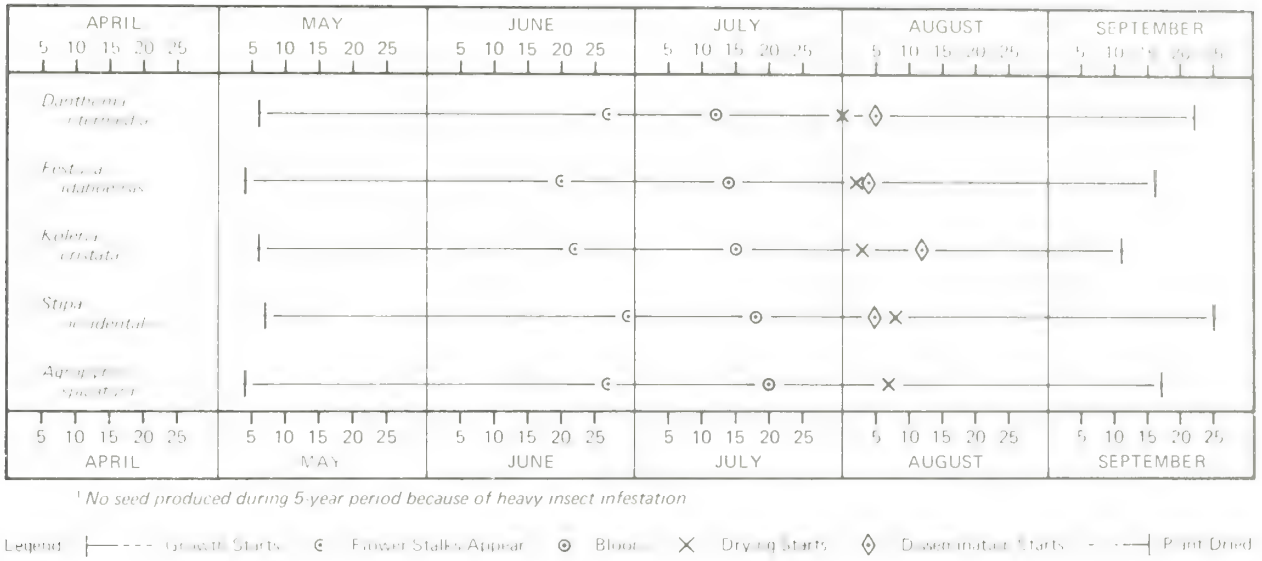

Figure 2.--The 5-year mean of developmental events for grasses on a southwest exposure at 7,100-ft. elevation.

The maximum difference between years in time of first bloom for the six early-flowering forbs ranged from 18 to 33 days (average was 22 days). This difference was about the same for the six forbs that bloom in midseason. However, the maximum difference between years in time of first bloom of the 11 late-flowering forbs ranged from 8 to 21 days and averaged only 12 days. The difference between the earliest and latest dates of full bloom corresponded closely to that for first bloom for all three groups of species. Apparently, temperature is a dominant factor in control of flowering of species that bloom early or in midseason. Retarding effects of a late spring and accelerating effects of an early spring are still effective in early June when the mid-season plants begin to flower, but have little effect by the time the late-blooming species start to flower in late June and early July. The reduced yearly variation in date of flowering of the late-blooming species could reflect this group's greater dependence on photoperiod than on temperature control of flowering.

The greatest difference between years in the date of flower stalk appearance for the grasses ranged from 10 days for *Danthonia* to 28 days for *Festuca*; it averaged 17 days for all five species studied (table 2). Yearly differences were reduced to an average of 11 days (6 days for *Agropyron* to 19 days for *Danthonia*) by the time these grasses flowered. Interestingly, the date of blooming for *Festuca* varied relatively little between years (8 days), and *Danthonia* varied greatly (19 days); this was just the opposite of the variation that existed when the flower stalks first appeared. Average elapsed time between first appearance of flower stalks and blooming was 14 days for *Danthonia*, 18 days for *Stipa*, and approximately 23 days for *Agropyron*, *Festuca*, and *Koeleria*.

The duration of flowering (fig. 1) denotes the time each species of forb had a floral aspect. The precise date of flowering differed between individual plants of the same species; this difference was much greater in some species than in others. *Lomatium* and *Achillea* prolonged their floral aspect over at least 4 weeks, whereas that of most species usually lasted 2 to 3 weeks.

Table 1.--*Earliest (E), latest (L), and mean (M) dates of developmental events for forbs on the southwest exposure at 7,100-ft. elevation over a 5-year period.*

Species	Code	Active growth starts	Flowering starts	Full bloom	Flowering over	Seed dissemination starts	Plant dried
Achillea millefolium	E	4/28	6/28	7/6	7/30	8/11	8/21
	L	5/12	7/15	7/21	8/31	9/4	9/27
	M	5/4	7/9	7/15	8/10	8/25	9/5
Agoseris glauca	E	4/28	5/22	5/26	6/1	6/15	7/9
	L	5/15	7/7	7/11	7/17	7/19	8/16
	M	5/5	6/8	6/12	6/17	7/1	7/25
Anemone patens	E	4/18	4/30	5/9	5/18	6/25	8/20
	L	5/10	5/18	5/24	6/2	7/16	8/30
	M	4/31	5/9	5/17	5/25	7/7	8/24
Antennaria rosea	E	5/3	6/18	6/24	7/8	7/24	--
	L	5/26	7/6	7/11	7/17	8/5	--
	M	5/15	6/29	7/6	7/14	7/28	--
Besseya wyomingensis	E	4/22	4/30	5/4	5/8	6/30	7/30
	L	5/10	5/18	5/26	6/2	7/20	8/10
	M	5/3	5/9	5/16	5/24	7/10	8/6
Campanula rotundifolia	E	5/1	7/15	7/20	7/28	8/13	8/21
	L	5/20	7/24	8/1	8/13	8/28	9/17
	M	5/12	7/19	7/24	8/5	8/19	9/2
Cerastium arvense	E	5/1	5/28	6/8	6/28	7/3	7/30
	L	5/20	6/27	7/1	7/12	7/20	9/5
	M	5/9	6/15	6/22	7/5	7/13	8/12
Comandra umbellata	E	5/1	6/19	6/28	7/2	([1])	9/6
	L	5/25	6/27	7/5	7/18		10/10
	M	5/13	6/22	7/2	7/11	8/14	9/22
Delphinium bicolor	E	4/21	5/22	6/6	6/28	7/2	7/8
	L	5/17	6/26	7/1	7/18	7/21	7/26
	M	5/4	6/11	6/20	7/8	7/13	7/19
Dodecatheon conjugens	E	4/28	5/5	5/11	5/15	([1])	6/20
	L	5/14	5/27	6/3	6/15		7/13
	M	5/5	5/17	5/24	6/4	6/4	7/5
Frasera speciosa	E	4/26	5/25	6/3	6/23	7/15	7/30
	L	5/16	6/18	6/28	7/6	8/1	9/2
	M	5/7	6/8	6/18	7/1	7/25	8/19
Fritillaria pudica	E	4/20	5/2	5/10	5/18	7/19	6/25
	L	5/13	5/25	5/30	6/10	7/27	8/5
	M	5/2	5/12	5/20	5/20	7/13	7/21

(con. next page)

Table 1.--(con.)

Species	Code	Active growth starts	Flowering starts	Full bloom	Flowering over	Seed dissemination starts	Plant [illegible]
Galium boreale	E	5/3	7/18	7/14	7/27	8/16	8/27
	L	5/24	7/18	7/25	8/14	9/8	9/18
	M	5/13	7/13	7/20	8/3	8/22	9/8
[illegible]	E	5/7	7/11	7/16	7/18	[illegible]	8/20
[illegible]	L	5/28	7/22	7/25	8/12	9/3	9/10
	M	5/18	7/15	7/21	8/1	8/22	8/30
[illegible]	E	4/26	5/29	6/6	6/10	7/11	8/16
triflorum	L	5/12	6/15	6/20	6/30	7/25	9/13
	M	5/4	6/6	6/14	6/21	7/20	8/27
Linum perenne	E	4/21	7/1	7/8	7/18	7/22	8/26
	L	5/22	7/12	7/25	8/5	8/18	9/24
	M	5/1	7/7	7/16	7/28	8/8	9/11
[illegible]	E	4/18	4/20	5/12	6/6	7/7	7/10
cous	L	5/10	5/23	5/30	6/27	7/21	7/26
	M	4/27	5/6	5/21	6/16	7/11	7/17
Lupinus serecius	E	5/14	6/24	7/1	7/14	8/1	8/12
	L	5/27	7/5	7/15	7/30	8/12	9/8
	M	5/22	6/30	7/8	7/24	8/5	8/27
[illegible]	E	4/18	6/12	6/25	7/2	8/2	8/11
[illegible]	L	5/12	7/3	7/10	7/19	8/18	9/30
	M	4/30	6/23	7/3	7/10	8/8	9/5
Pedicularis	E	5/1	7/1	7/6	7/15	7/22	8/4
[illegible]	L	5/21	7/14	7/19	7/27	8/11	9/2
	M	5/10	7/5	7/12	7/21	8/3	8/25
Polygonum bistortoides	E	4/26	6/8	6/15	6/29	7/4	7/20
	L	5/12	6/20	7/1	7/14	7/20	8/2
	M	5/4	6/13	6/22	7/7	7/14	7/27
Saxifraga montanensis	E	4/18	5/12	5/18	6/1	7/7	7/11
	L	5/10	6/2	6/6	6/26	7/27	7/26
	M	4/30	5/21	5/31	6/15	7/16	7/19
Zygadenus	E	4/18	6/23	7/2	7/7	7/26	[illegible]
[illegible]	L	5/10	7/1	7/8	7/16	8/12	8/14
	M	4/28	6/27	7/5	7/12	8/3	7/29

[1]Seed set in only 1 of the 5 years.

Table 2.--*Earliest (E), latest (L), and mean (M) dates of developmental events for grasses on the southwest exposure at 7,100-ft. elevation over a 5-year period.*

Species	Code	Active growth starts	Flower stalks appear	Flowers in bloom	Seed dissemination starts	Drying begins	Plants dried
Agropyron spicatum	E	4/25	6/18	7/19		7/23	9/6
	L	5/15	7/3	7/25	(1)	8/30	9/28
	M	5/4	6/27	7/20		8/7	9/17
Danthonia intermedia	E	5/1	6/22	7/1	7/25	7/20	9/8
	L	5/20	7/2	7/20	8/15	8/20	10/12
	M	5/6	6/27	7/12	8/5	7/31	9/22
Festuca idahoensis	E	4/25	6/2	7/10	7/25	7/23	8/27
	L	5/16	6/30	7/18	8/10	8/20	10/12
	M	5/4	6/21	7/14	8/4	8/3	9/16
Koeleria cristata	E	4/25	6/7	7/6	7/31	7/20	8/21
	L	5/17	6/28	7/20	8/25	8/20	10/7
	M	5/6	6/22	7/15	8/12	8/3	9/11
Stipa occidentalis	E	5/1	6/23	7/14	7/28	7/30	9/3
	L	5/18	7/5	7/22	8/14	8/20	10/20
	M	5/7	6/29	7/18	8/5	8/8	9/25

[1]Maturing seed destroyed by insects.

The interval between cessation of flowering and the beginning of seed dissemination differed greatly among forbs. *Delphinium* seed began to disseminate an average of only 5 days after flowering, but more than 40 days elapsed before the seed of *Anemone*, *Besseya*, and *Fritillaria* began to fall. These intervals were typically much shorter for late-flowering species (average, 17 days) than for the early bloomers (average 36 days). Usually, grasses began to drop seed between 18 and 28 days after flowering.

Maximum differences between years in date of seed dissemination ranged from 8 to 44 days, according to species; the average was about 20 days regardless of whether the plants were early or late bloomers. Date of seed dissemination for *Fritillaria* was least variable from year to year (8 days). Species that showed the greatest yearly variation were *Agoseris* (44 days), *Galium* (33 days), and *Linum* (27 days).

Different species dried at widely different times. Those that bloomed early usually dried earlier than those that bloomed late, but there were several exceptions; for example, both *Besseya* and *Anemone* bloomed very early (mid-May), but usually did not dry until early and late August, respectively. Conversely, *Zygadenus* bloomed in early July and was usually dry by the end of that month. Although the grasses usually began to dry in early August, they did not reach the dry stage until approximately the middle of September. *Comandra* and the grasses were the last species to dry. The leaves of *Antennaria* apparently remained viable beyond the growing season in which they were formed. *Agoseris* and *Frasera* plants that flowered generally dried much sooner than those that remained in a strictly vegetative condition.

The maximum difference between years in date of drying of various species ranged from 10 to 51 days. Generally, the later a plant flowered, the greater the difference in date of drying between years. The average difference between the earliest and latest drying dates was 19 days for early bloomers, 29 days for midseason bloomers, 33 days for late bloomers, and 39 days for the grasses.

The average length of time that plants remained photosynthetically active ranged from 62 days for *Dodecatheon* to 147 days for *Danthonia* (table 3). This active period was considered to extend from the onset of spring growth until the species dried. A general relationship existed between time of flowering and the length of time that plants remained active: early bloomers, 86 days; midseason bloomers, 94 days; late bloomers, 115 days; the early-flowering *Anemone*, midseasonal *Delphinium*, and late *Lupinus* were conspicuous exceptions to this generality (table 3). The grasses remained active for by far the longest period (an average of 137 days). Active growth for all forbs and grasses averaged 108 days.

Table 3.--*Shortest, longest, and mean periods (in days) of photosynthetic activity over 5 years for plants on the southwest exposure at 7,100 ft.*

Species	Shortest	Longest	Mean	Species	Shortest	Longest	Mean
[illegible]	50	76	62	[illegible]a	76	127	110
Delphinium bicolor	71	89	79	[illegible]	98	131	115
Fritillaria pudica	66	102	80	*Anemone patens*	105	126	116
Saxifraga montanensis	74	93	80	[illegible]	111	127	118
Agoseris glauca	72	98	81	[illegible]	101	150	124
[illegible]	77	95	84	*Koeleria cristata*	96	159	127
Polygonum bistortoides	81	97	84	*Oxytropis sericea*	101	152	128
Zygadenus venenosus	69	107	92	*Comandra umbellata*	118	140	132
Cerastium arvense	83	127	95	[illegible]	151	151	136
Besseya wyomingensis	91	99	95	[illegible]	117	146	138
Lupinus sericeus	90	108	99	[illegible]	120	169	138
Gaillardia aristata	86	128	104	[illegible]	111	160	139
Pedicularis contorta	93	121	106	[illegible]	130	164	147
Frasera speciosa	99	122	110				

Over the 5 years, differences between the shortest and longest periods of active growth averaged 28 days for forbs and 43 days for the grasses. Generally, the period of active growth varied least between years for those species that have short growth periods; it varied most for those species that have long growth periods.

Although most species apparently became dormant for the remainder of the year following drying, several produced new leaves again in the fall. *Geum*, *Saxifraga*, *Cerastium*, and the five grasses shown in figure 2 had this habit. Fall regowth in *Geum* and *Saxifraga* was in the form of a small rosette of new leaves within the outer rosette of dried leaves. Holway and Ward (1965) noted this characteristic on *Saxifraga rhomboidea* growing in alpine tundra. Regrowth of *Cerastium* was in the form of small leaves in the axils of the dried leaves distributed along the stems. This regrowth usually persisted over winter and appeared to become active again when growth resumed the following spring.

Plant development was delayed on northeast exposures and at the higher elevation (table 4). Some species were affected by these environmental differences much more than others. Depending on species, the start of growth averaged 3 to 12 days later on northeast exposures than on southwest exposures. *Oxytropis* was an exception; start of growth for this species was delayed an average of 18 days. The general trend was for plants to develop about 1 week later on northeast exposures than on southwest exposures. This difference persisted throughout the growing season. Costello and Price (1939) observed that development on north exposures lagged about 10 days behind that on south exposures on mountain herblands in Utah, whereas Bliss (1956) found only a 2- to 4-day lag on north exposures in the alpine tundra of southern Wyoming.

For individual species, a 1,100-ft. elevational difference delayed beginning of growth from 19 to 37 days (table 4), an average delay of 28 days for all species. Plants at the higher elevation generally developed more rapidly than those at the lower; by the time of flowering, this delay was reduced to an overall average of only 21 days. At the 8,200-ft. elevation, plants dried an average of only 16 days later than at 7,100 ft. The lag in plant development attributed to elevational rise in this study is considerably greater than the 10 days per 1,000 ft. suggested by Hopkins' Bioclimatic Law (Hopkins 1938). It is also greater than the average 12 days per 1,000 ft. observed by Costello and Price (1939) in the mountains of Utah and the average 10-day delay in lilac bloom for each 1,000-ft. elevational rise in Montana (Caprio 1966). This difference in findings might be the result of unusually late snowmelt at the higher elevations on this study area in southwestern Montana. Costello and Price (1939) found that date of snowmelt and onset of growth were closely related, and Holway and Ward (1965) considered snow cover the primary factor influencing phenology of alpine tundra. The response of individual species to elevational differences varied considerably, as Costello and Price (1939) also observed. Growth of *Antennaria* and *Stipa* appeared least affected by elevational differences. The beginning of growth for these two species was delayed only about 20 days; flowering of *Stipa*, 15 days, and of *Antennaria*, 11 days. Growth of *Lomatium* appeared to be most affected by elevation; both the start of growth and flowering of this species were delayed an average of 37 days by the 1,100-ft. increase in elevation.

Differences between exposures in the duration of plant growth varied greatly among both species and years. This was also true for differences between elevation. No consistent overall difference in growth duration was apparent between exposures; however, the growth period was generally about 1 week shorter at 8,200-ft. than at 7,100-ft. elevation. For species common to both elevations, the growth period averaged 94 days at 8,200 ft. and 103 days at 7,100 ft.

Table 4.—[illegible]

exposures, and at 8,200 ft. as compared to 7,100-ft. elevation[1]

Species	Exposure						Elevation					
	Growth starts		Bloom		Dried		Growth starts		Bloom		[illegible]	
	x	σ	x	σ	x	σ	x	σ	x	σ	x	σ
FORBS:												
Achillea millefolium	7	7	2	5	2	17	32	10	21	11	20	24
Agoseris glauca	9	4	11	12	21	25	26	9	26	13	34	25
Anemone patens	10	2	10	2	5	12						
Antennaria rosea	9	6	5	3	--	--	20	6	11	7		
Arenaria macrophylla	7	6	2	4	4	10						
Cerastium arvense	5	3	2	4	11	11	27	8	24	7	6	15
Delphinium bicolor	5	8	8	5	2	7	29	12	19	12	13	10
Dodecatheon conjugens	7	5	9	6	17	12	28	9	29	8	25	11
Erigeron gracilis	4	2	4	4	1	15						
Fritillaria pudica	6	5	7	7	4	8						
Gaillardia aristata	8	9	4	1	9	5						
Geum triflorum	6	6	6	6	8	12	24	10	22	8	20	10
Linum perenne	7	10	5	1	9	5						
Lomatium cous	11	4	11	7	5	3	37	10	37	10	14	5
Lupinus argenteus	7	6	5	6	1	4						
Lupinus serecius	8	2	5	5	2	5						
Myositis sylvatica							30	8	20	5	24	10
Osytropis serecia	18	5	10	5	2	20	30	13	19	7	15	11
Phlox multiflora	7	4	-1	4	7	4	28	5	15	6	8	12
Polygonum bistortoides	7	5	5	5	5	5	29	9	17	6	14	6
Potentilla diversifolia	7	5	5	2	12	12						
Saxifraga montanensis	9	5	13	6	7	5	32	5	29	8	4	2
Frasera speciosa							28	14	19	8	15	14
Zygadenus veneosus	12	10	9	6	15	17						
GRASSES:												
Agropyron spicatum	11	4	2	4	5	9						
Agropyron caninum	8	1	1	2	6	2						
Danthonia intermedia	9	9	1	3	2	3	24	8	13	7	6	7
Festuca idahoensis	7	5	4	4	9	16	27	10	16	5	17	24
Stipa occidentalis	7	6	4	4	6	12	19	7	15	8	8	14

[1]Data from lower and upper elevations combined to determine differences between exposures: those from southwest and northeast exposures combined to determine differences between elevations.

HERBAGE PRODUCTION

Production of vegetation differed between exposures and fluctuated considerably over the years. Although production was usually greater on the northeast exposures, the magnitude of this difference varied with both elevation and year. Over the 5-year study, the southwest exposure produced only 58 percent as much herbage as the northeast exposure at 7,100-ft. elevation, whereas at 8,200 ft., it produced 90 percent as much herbage as the northeast exposure. Composition of this vegetation also differed between exposures, but again this difference was not consistent between elevations. At the lower elevation, graminoids formed 58 percent of the total production on the southwest exposure and 26 percent on the northeast exposure. At the upper elevation, these proportions were reversed; graminoids formed 36 percent of the vegetation on the southwest exposure and 58 percent on the northeast exposure.

Herbage production generally fluctuated more between years on northeast than on southwest exposures. Total production on the northeast exposure at 7,100-ft. elevation averaged 1,246 lb./acre with a coefficient of variation (C) of 26 percent; at 8,200-ft. elevation, it averaged 1,127 lb./acre with a C of 25 percent. However, on southwest exposures, total production at 7,100 ft. averaged 724 lb./acre with a C of only 11 percent; at 8,200-ft. elevation, production averaged 1,021 lb./acre with a C of only 16 percent. The forbs were primarily responsible for this greater variation in total production on the northeast exposures; the C for forbs averaged 36 percent on the two northeast exposures, and only 17 percent on the two southwest exposures. Variability of graminoid production over the 5 years was about the same on both exposures and at both elevations (C ~ 20 percent).

The amount of variation in production of individual species at the two lower elevation areas is shown in table 5. These data also exemplify production differences between exposures, which were on facing slopes within 200 yards of each other. Relative production of most species fluctuated considerably more between years than did production by vegetation classes. This finding supports Blaisdell's (1958) conclusions that (a) individual species vary greatly in their response to the same environmental factors and (b) increased yield of one can compensate for decreased yield of another and thus dampen oscillations in total production. The great difference between years in relative amounts of minor species (those that contribute little to overall production) is probably the result of sampling inadequacies.

Since 5 years of both production and weather records were available from all four areas, I had an opportunity to relate weather variations to yearly variations in plant production. I assumed at the outset that differences in productive capacity existed between the four areas, irrespective of yearly variations in weather. These area differences were discounted prior to analyses for weather effects. Production for an area

Table 5.--[illegible] *at 7,100-ft. elevation*

Species	Southwest exposure			Northwest exposure		
	High	Low	Mean	High	Low	Mean
	Lb./acre, air dry					
Total vegetation	817.5	604.7	723.6	1,599.2	723.8	1,246.4
Total graminoids	532.3	326.2	422.7	405.7	203.4	319.0
Total forbs	374.3	246.4	300.9	1,294.6	520.4	927.4
GRAMINOIDS						
[illegible]	126.6	59.5	85.7	98.8	37.6	54.3
Agropyron caninum	2.6	0.1	1.2	9.8	2.3	5.3
Bromus anomalus				14.8	7.0	11.0
Carex filifolia	43.0	28.1	36.1	12.2	5.8	9.1
Carex stenophylla	17.5	11.4	13.6	23.8	3.0	11.5
Danthonia intermedia				58.2	5.5	32.9
Festuca idahoensis	333.3	202.0	257.3	155.2	73.4	131.9
Koeleria cristata	16.2	10.5	13.8	13.1	2.8	5.8
Poa spp.				4.9	.2	2.2
Stipa occidentalis	26.3	4.8	14.8	81.0	22.3	56.9
FORBS						
Achillea millefolium	21.9	9.3	13.7	48.6	11.5	27.5
Agoseris glauca	24.6	12.9	21.1	10.4	1.3	5.4
Anemone patens	4.9	1.5	3.0	39.6	6.2	24.5
Antennaria rosea	21.6	8.7	16.5	12.8	2.8	9.4
Arenaria congesta	18.1	.8	8.7	69.8	2.7	38.9
Astragalus miser	8.3	1.3	3.2	10.9	2.3	5.5
Besseya wyomingensis	2.3	.7	1.1			
Campanula rotundifolia	14.1	8.3	11.2	28.2	4.3	15.3
Cerastium arvense	23.2	14.8	18.5	91.6	23.2	60.4
Clematis hirsutissima				18.3	4.5	11.2
Comandra umbellata	5.3	1.8	3.0			
Erigeron subtrinervis	13.7	1.4	7.8	115.7	37.8	75.7
Eriogonum umbellatum				89.4	38.9	53.7
Frasera speciosa	34.4	12.8	22.3	3.3	.6	1.7
Fritillaria pudica				.6	.1	.2
Gaillardia aristata	27.0	12.2	18.4	67.5	11.6	27.5
Galium boreale	65.4	36.8	50.5	48.8	17.4	27.8
Gentiana affinis	11.2	1.9	4.8			
Geranium viscosissimum				165.8	63.8	102.0
Geum triflorum	12.8	5.7	8.8	139.3	45.2	97.3
Gilia congesta	6.4	.4	2.6			
Linum perenne	26.7	5.8	19.6	7.8	2.3	5.9
Lupinus serecius				234.6	98.1	142.1
Myositis sylvatica				20.8	2.6	12.0
Oxytropis serecia	5.8	1.0	3.3			
Pedicularis contorta	58.9	37.4	45.5			
Phlox hoodii	3.2	.5	2.1			
Phlox multiflora	3.1	.1	1.3	105.4	74.9	87.6
Polygonum bistortoides				6.1	1.4	3.5
Potentilla gracilis				20.0	4.1	8.3
Taraxacum officinale	3.1	.8	2.0			
Townsendia mensana	2.8	1.0	1.9			
Viola adunca				112.5	40.8	77.5
Zygadenus venenosus	2.4	.1	1.1	9.6	1.3	4.7

in each of the 5 years was adjusted by the ratio of individual area mean to the all-areas mean; if the interaction between weather and site effects is minimal, this adjustment should effectively discount inherent differences in site productivity. Adjusted productions of total graminoids, of total forbs, and of total vegetation were then evaluated against selected weather factors.

Various expressions of precipitation, air and soil temperatures, solar radiation, wind, and soil moisture status in different months were examined for possible linear relationships to herbage production. Fifty-three such independent variables were examined. From these, I selected the 16 shown in table 6 as possibly being related singly or in combination to the amount of herbage produced every year. The measurement units for these 16 independent variables are:

Soil moisture	-- logarithm of ohms electrical resistance;
Precipitation	-- accumulated inches for given period;
Solar radiation	-- average cal./cm.^{2}/day for given period;
Air temperature	-- daily maximum °F. averaged for given period;
	-- daily minimum °F. averaged for given period;
	-- degree-hours (the daily average of hours the temperature remained within 5° F. of the extreme, multiplied by the extreme);
Soil temperature	-- same measurement units as air temperature, but measured on a shaded soil surface;
Wind velocity	-- average miles per hour for given period.

Few of these variables were independently correlated significantly with the production of either graminoids, forbs, or total vegetation in this limited test. Consequently, the significant positive correlation of production with May precipitation and the negative correlation with the maximum temperatures of the shaded soil surface are particularly conspicuous (table 6). Earlier, I observed that total production on similar mountain grasslands may be related more closely to precipitation falling during the period of most active growth than to precipitation at other times (Mueggler 1967). Smoliak (1956) found production on the short-grass prairies of Alberta to be highly correlated (r = 0.86) with May-plus-June precipitation, and significantly negatively correlated (r = -0.53) with seasonal mean temperatures. Failure to verify suspected correlations with soil moisture at the beginning of plant growth might be explained by the small variation in soil moisture between years. Soils on these grasslands usually are near their maximum moisture-holding capacity, down to a depth of 50 cm. at least, at the beginning of plant growth (Mueggler 1971). Ordinarily, this is also true down to 100-cm. depths on northeast exposures, but not on southwest exposures. The negative correlation with maximum temperatures of the shaded soil surface and positive correlation with minimum air temperature (degree-hours) suggests that growth of these mountain grassland plants may be favored somewhat by rather cool weather in June and July.

I tested various combinations of independent variables by multiple regression analyses to determine the combination that would best predict herbage yield. A combination of the five following weather measurements gave the highly significant coefficient of multiple determination (R^2) of 0.86 when correlated with total herbage yield: X_3, May precipitation; X_7, maximum air temperature (°F.) in July; X_8, maximum air temperature (degree-hours) in June; X_{11}, minimum air temperature (degree-hours) in June; and X_{14}, maximum temperature (degree-hours) of shaded soil surface in June. The equation used to estimate total herbage production (Y_1) has a standard error of estimate of 83 lb./acre (mean production = 1,030 lb./acre):

$$\hat{Y}_1 = 1{,}194 + 169X_3 - 19.2X_7 - 2.31X_8 + 2.40X_{11} + 3.50X_{14}.$$

Table 6.--*Simple correlation coefficients (r) between herbage production and selected weather measurements*

Independent variable		Production		
		Graminoids	Forbs	Total herbage
	Soil moisture at beginning of growth:			
X_1	Weighted average for soil mantle	-0.13	-0.06	-0.10
X_2	at 50-cm. depth	-.12	-.20	-.20
	Precipitation:			
X_3	May	.54*	.65**	.70**
X_4	May through July	.22	.38	.41
	Solar radiation:			
X_5	June	-.16	-.21	-.25
	Maximum air temperatures (°F.):			
X_6	June	-.03	-.36	-.27
X_7	July	-.15	-.24	-.25
	Maximum air temperatures (degree-hours):			
X_8	June	-.21	-.06	-.15
X_9	July	-.31	-.28	-.34
	Minimum air temperatures (°F.):			
X_{10}	June	.10	.09	-.01
	Minimum air temperatures (degree-hours):			
X_{11}	June	.14	.54*	.48*
	Maximum temperatures of shaded soil (°F.):			
X_{12}	June	-.38*	-.62**	-.61**
X_{13}	July	-.46	-.50*	-.57**
	Maximum temperatures of shaded soil (degree-hours):			
X_{14}	June	.02	-.23	-.16
	Wind velocity:			
X_{15}	June	.04	-.26	-.18
X_{16}	July	-.20	-.19	-.24

*Significant
**Highly significant

A different combination of five weather variables gave a highly significant R^2 of 0.74 when correlated with total production of forbs. The five independent variables in this case were: X_3, May precipitation; X_5, solar radiation in June; X_6, maximum air temperature (°F.) in June; X_{10}, minimum air temperature (°F.) in June; and X_{12}, maximum temperature (°F.) of shaded soil surface in June. Total forb production (Y_2) can be estimated with a standard error of estimate of 93 lb./acre (mean production = 590 lb./acre) using the following equation:

$$\hat{Y}_2 = 1{,}039 + 95.2X_3 + 2.29X_5 - 55.6X_6 + 70.6X_{10} - 18.2X_{12}.$$

Equations developed for predicting total production of graminoids were considerably less precise than those used to predict production of either total vegetation or total forbs. To predict total graminoid production, a combination of four weather measurements was superior to any combination of five tested. The following four independent variables gave a significant R^2 value of 0.52: X_3, May precipitation; X_7, maximum air temperature (°F.) in July; X_{15}, wind velocity in June; and X_{16}, in July. The equation derived for predicting total graminoid production (Y_3) from these four variables has a standard error of estimate of 60 lb./acre (mean production = 439 lb./acre):

$$\hat{Y}_3 = -415 + 103X_3 + 6.91X_7 + 64.7X_{15} - 41.0X_{16}.$$

The correlation coefficients and regression equations examined in this paper are based upon rather tenuous data for meaningful regression analyses. However, they do give some indication of which weather variables may be influential in determining the large yearly variations in herbage production on these mountain grassland ranges.

MANAGEMENT IMPLICATIONS

Range managers generally rely upon vegetation and soil readiness indicators to decide when grazing can safely begin in the spring or early summer. Two common indicators of vegetation readiness on mountain grasslands in Montana are *Delphinium bicolor* in full bloom and appearance of *Festuca idahoensis* flower stalks (USDA Forest Serv. 1969). When these indicators were applied to this study, the date of vegetation readiness for grazing was found to differ as much as 26 days during the 5 years. Weather conditions were not extreme during this period; a greater difference will likely occur over a longer time. However, in 2 out of 3 years, vegetation should be ready to graze within 11 days of the average date of readiness, judging from the variability (σ = 11.2) in date of readiness over the 5 years studied.

Although the lag in plant development attributable to each 1,000-ft. rise in elevation is generally considered to be about 10 days (Hopkins' Bioclimatic Law), the lag apparently can be much greater in some of our mountain areas. In this study, the lag in plant development (and consequently in vegetation readiness for grazing) was 18 days/1,000-ft. rise in elevation. We can also expect a lag of almost 1 week in vegetation readiness on north exposures compared to south exposures.

Knowing how much herbage production is likely to vary from year to year assists the range manager (a) in establishing grazing capacities and (b) in anticipating possible yearly adjustments in stocking. This study shows that herbage production differs much more between years on north exposures than on south exposures. Over this one 5-year period, more than twice as much vegetation was produced on northeast exposures during the high year than during the low year; during this same period, only one-third again as much vegetation was produced on southwest exposures during the high year than the low. Generally, production of forbs varies more between years than production of grasses. In 2 out of 3 years, total herbage production on northeast slopes can be expected to be within 26 percent and that on southwest slopes to be within 14 percent of their respective mean productions.

Regression equations developed in this study for predicting production based upon weather data are primarily of theoretical value. The resource manager seldom has access to these types of weather data collected on mountain rangelands. However, both the positive relationship established between production and May precipitation and the negative relationship between production and maximum temperatures in June and July have practical significance. In years when May precipitation is above normal and June and July daytime temperatures are below normal, above-average herbage production can be expected. Conversely, when May precipitation is below normal and June and July temperatures are above normal, below-average herbage production can be expected.

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Plant development and yield data collected over a 5-year period are summarized. Differences between years, elevations, exposures, and species are discussed. Yield differences between years are evaluated with respect to differences in weather.

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BITTERBRUSH TOPPING:

SHRUB RESPONSE AND COST FACTORS

Robert B. Ferguson

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Ogden, Utah 84401

COVER PHOTO: A forestry technician uses a lightweight chain saw to "top" overmature bitterbrush near Irish Creek, Boise National Forest.

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Research conducted cooperatively by Intermountain Forest and Range Experiment Station, USDA Forest Service, Ogden, Utah, and the Idaho Fish and Game Department through Federal Aid to Wildlife Restoration Project W-111-R.

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The following personnel assisted in collecting data: BOISE NATIONAL FOREST — Darwin R. Jensen, former Range Conservationist, Ervol I. Sheffield, Fire Control Officer, Abb H. Taylor, Range Conservationist, and William L. Thompson, former Assistant District Ranger, Cottonwood Ranger District; MODOC NATIONAL FOREST — Dewey G. Riscioni, Assistant District Ranger, Doublehead Ranger District, Sherwood L. S. Stutz, Wildlife Biologist, and Ray L. Ward, Range Conservationist; SAWTOOTH NATIONAL FOREST — Roderick R. Howard, former Range Conservationist, William J. Little, former Range Conservationist, Lewis A. Munson, District Ranger, Twin Falls District, and Donald J. Proctor, Range Conservationist; PACIFIC SOUTHWEST FOREST AND RANGE EXPERIMENT STATION — Donald L. Neal, Range Scientist, and Thomas F. Newman, Wildlife Biologist; IDAHO FISH AND GAME DEPARTMENT — Gary R. McNeill, Regional Game Manager; INTERMOUNTAIN STATION — Douglas G. Mefford, former Range Research Technician, and Thomas E. Olsen, former Range Aid.

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ABSTRACT

Methods of topping overmature bitterbrush shrubs and the subsequent effect on annual twig growth were studied on three widely separated deer winter ranges. Annual twig growth increased considerably following topping, then gradually decreased, although it remained greater than on untopped shrubs during the 4 years of study. No detrimental effects on shrub longevity, nor increase in damage from insect attack or disease were observed. Chain saws were more efficient than hand tools for topping. Using chain saws, an efficient crew should be able to top a stand of bitterbrush, similar in density to those described, for $9.00 to $21.00 per acre.

INTRODUCTION

Bitterbrush, *Purshia tridentata* (Pursh) DC., a deciduous shrub native to much of the Intermountain West, generally is an important component of the winter diet of deer. From 1959 to 1963, an exploratory study was conducted near Boise, Idaho, to determine the effect of topping on subsequent annual twig production of overmature bitterbrush shrubs (Ferguson and Basile 1966). Removal of a considerable portion of the shrub canopy resulted in a substantial increase in annual twig production.

As a followup to this initial effort, a more comprehensive study was planned to evaluate shrub response under a wider variety of environmental conditions. Also, methods of topping and the economic feasibility of large-scale topping projects were assessed.

In the spring of 1966, the Boise, Modoc, and Sawtooth National Forests participated with the Intermountain Forest and Range Experiment Station in a field test of the topping technique. This paper reports on both shrub response and factors affecting the cost of topping. Some observations on shrub longevity and the effect of repetitive topping are also presented.

METHODS

The purpose of topping is to stimulate profuse twig growth from live branches below the level at which the old shrub is cut off. The treatment was applied only once, and the magnitude of twig production assessed following each of the subsequent four growing seasons.

Figures 1 through 3 illustrate the three study areas and table 1 tabulates descriptive information about them. The overmature bitterbrush shrubs (those that have reached an age at which annual twig production is small compared to that of young shrubs) were slightly larger in height and canopy spread on the Boise site than on either of the other study sites. Shrubs on the Modoc area tended to branch more from the base and, on the whole, were more vigorous. Many of the old shrubs on the Sawtooth area were of small stature, possibly because they were growing along a ridge site.

Topping was accomplished the last week of March 1966 on the Boise and Sawtooth sites, and during the third week in April on the Modoc. Treatment was completed before flower buds developed. (New twig growth does not begin on bitterbrush until the flowering stage is nearly complete.) Approximately 10 acres were treated at each site.

Each study area was divided into four sections. Lightweight, direct drive chain saws were used on two sections and lopping shears on the alternate two sections. Overmature shrubs, 5 to 7 feet tall, were cut off 3 to 4 feet above the ground. Smaller overmature shrubs, more common on the Sawtooth site, were cut so as to remove about one-half of the canopy volume. All shrubs were cut on a horizontal plane through the canopy.

Prior to topping, 20 shrubs were chosen at random from the stand on each study area. These old shrubs were randomly divided and assigned to either the topped or the control shrub group. The topped shrubs were cut at the time the stands were treated. All sample shrubs were marked by numbered aluminum tags and plastic flagging. Following topping, a complete count was made of all shrubs on each study area.

At the end of each growing season (1966 through 1969), all annual twigs 0.2 inch long or longer were measured on two branches of each sample shrub. Measurements were started at a point where the diameter of the branch was approximately 1 inch. These branches had also been selected and tagged prior to topping to preclude bias in their selection. The same branches were remeasured each year, unless flagging and tags had been torn off by deer or a branch had died. In these few instances, new sample branches were chosen.

Figure 1.--Boise study area, Boise National Forest, Boise County, Idaho.

Each fall, an estimate was also made of the percent of the entire canopy made up by the two sample branches. For example, if the total twig growth on the two branches of a particular shrub was 300 inches, and the estimator believed that these two branches made up 10 percent of the entire shrub, then there might be about 3,000 linear inches of twig growth on that shrub.

The percent dead canopy of each sample shrub was estimated to the nearest 10 percent prior to topping, and was reestimated each year thereafter.

Figure 2.--Sawtooth study area, Sawtooth National Forest, Twin Falls County, Idaho.

Figure 3.--Modoc study area, Modoc National Forest, Modoc County, Calif.

Data obtained annually from the sampled shrubs on each study area were tested for homogeneity of variance by Bartlett's test. When variance was not homogeneous, a *t* test described by Steel and Torrie (1960) was used to test for significant difference between means. When variance was homogeneous, the *t* test described by Dixon and Massey (1951) was used.

Use of the estimated percent of shrub canopy comprised of the two measured branches permitted a calculation of the annual growth for each sample shrub.

Table 1.--*Descriptive features of three study areas used to assess the effects of topping overmature bitterbrush shrubs*

Study area	Location	Elevation	Aspect and slope	Soil parent material	Annual precipitation	Mean no. shrubs topped per acre
		Feet			*Inches*	
Boise	18 miles east of Boise, Idaho	3,400	SE, 5-30%	Granite	18	155
Sawtooth	18 miles south of Twin Falls, Idaho	5,800	SE, 0-20%	Rhyolite	11	220
Modoc	20 miles south of Tule Lake, Calif.	4,300	Level	Basalt	11	546

RESULTS

Annual Twig Production

The response to topping was similar to that observed in earlier work (Ferguson and Basile 1966). Twig production on the branches sampled increased severalfold the first growing season after topping, then decreased each succeeding year (table 2).

The data on inches of twig growth can be roughly converted to ovendry weight by using a factor of 0.0809 pound per 1,000 inches of twig growth. This factor represents the mean of 19,600 twigs collected from 1,490 shrubs in southern Idaho. By using the mean shrub density (table 1) and the calculations of total twig growth per shrub, the pounds of forage produced per acre can be calculated. Table 3 shows productivity per acre (assuming either that all shrubs were untopped or that all were topped) and the gain in pounds per acre that resulted from topping.

Cost Per Acre

The cost of topping a bitterbrush stand will depend on a number of variables:

1.--Wages of personnel assigned to the work;
2.--experience of workers in the use of tools, particularly, the chain saw;
3.--dependability of workers in doing assigned work efficiently and conscientiously;
4.--density and size of overmature shrubs;
5.--roughness of the terrain;
6.--availability of lightweight chain saws and protective apparel; and
7.--distance to and from work.

Interaction of the first five of the above factors is reflected in the data shown in table 4 for the three sites treated in 1966. On the Modoc site, calculated cost per acre was $18.56 when topping was done by chain saws and $33.50 when lopping shears were used. Calculations included all costs charged to the project, including travel time. In this case, saws and protective apparel were available. If $3.75 per man-hour is used as a reasonable wage, topping could cost from $20.62 to $35.62 per acre when lopping shears are used. If chain saws are employed, topping could cost from $9.00 to $21.00 per acre. Most likely, the cost per acre will depend primarily upon the worker's skill in handling and servicing equipment and upon the density of shrubs to be cut.

Table 2.--*Mean twig growth on sample branches of 10 topped and 10 control bitterbrush shrubs over four growing seasons and the ratio of topped to control shrubs*

Year	Topped[1]	Standard deviation	Control	Standard deviation	Ratio
	Inches		*Inches*		
			BOISE		
1966	389**	196	75	97	5.2
1967	358	242	155	352	2.3
1968	186	104	111	125	1.7
1969	166	103	145	231	1.3
			SAWTOOTH		
1966	296**	147	48	55	6.2
1967	187**	74	45	55	4.1
1968	95**	49	32	45	3.0
1969	188	146	112	113	1.8
			MODOC		
1966	541*	337	225	102	2.4
1967	768**	430	332	118	2.3
1968	183	163	120	96	1.5
1969	239	241	154	145	1.5

[1]Asterisks denote significantly greater production than control shrubs (** = 0.01 level, * = 0.05 level).

Table 3.--*Pounds per acre of forage (ovendry) produced, assuming either topping or no topping, and the increase in available forage that resulted from topping*

Year	No shrubs topped	All shrubs topped	Gain from topping
		BOISE	
1966	12	84	72
1967	11	61	50
1968	19	35	16
1969	32	34	2
		SAWTOOTH	
1966	5	56	51
1967	5	33	28
1968	3	16	13
1969	8	44	36
		MODOC	
1966	75	180	105
1967	77	388	311
1968	36	76	40
1969	42	79	37

Table 4.--*Man-hours of work per acre and number of shrubs topped per man-hour on three study areas, 1966*

Study area	Topping method		
	Lopping shears	Chain saws[1]	
		Cutting time	Total time
	MAN-HOURS PER ACRE		
Boise	5.5	1.3	2.4
Sawtooth	6.4	1.6	3.9
Modoc	9.5	3.1	5.6
	SHRUBS PER MAN-HOUR		
Boise	30	112	61
Sawtooth	36	133	55
Modoc	50	201	109

[1]Total time includes time required for saw maintenance and for somewhat more frequent rest periods than when shears were used.

Effects on Shrub Condition

Four and one-half years after the topping treatment none of the sample shrubs were dead, and no obvious shrub mortality had occurred in the treated stands. Estimates of the percent of dead canopy indicated no appreciable differences between topped and control shrubs (table 5).

Table 5.--*Mean percent dead canopy*[1] *of topped and control bitterbrush shrubs before topping and four growing seasons later*

Study area	Topped shrubs		Control shrubs	
	March 1966	October 1969	March 1966	October 1969
Boise	6.0	13.0	10.0	10.5
Sawtooth	8.0	18.0	3.5	24.0
Modoc	10.0	20.0	10.0	25.0

[1]Based on estimated percent dead canopy of 10 topped and 10 control shrubs at each location.

DISCUSSION

Shrub Response

The response of overmature bitterbrush shrubs to topping on the three widely separated sites substantiated the previous findings of the 1960 tests near Boise. Environmental conditions in a particular year will affect overall shrub response on each site. Variation in the vigor of individual old shrubs will result in obvious differences in total amount of twig growth produced following topping.

Some twigs produced on tall, overmature bitterbrush shrubs are above the reach of deer. Thus, the calculated amounts of available forage shown for an untopped stand in table 3 are somewhat liberal. On the other hand, for several years following topping, virtually all twig production is available to deer. Of the three study areas involved, the Boise site probably had the highest proportion of tall shrubs. Shrubs on the Sawtooth site were generally smaller than those on either the Boise or the Modoc site.

If the sample shrubs were representative of the productivity of most shrubs on the three study areas, the Modoc site was by far the most productive (table 3). A bitterbrush stand such as that on the Modoc may not appear to need treatment to increase available forage. However, the Modoc results indicate the large increase in browse production possible from shrubs growing on a favorable site. At the other extreme, a stand similar to that on the Sawtooth site may be producing relatively small amounts of browse; so the increase in production that follows topping becomes important to wintering deer. Any decision as to whether or not topping is a justifiable practice will depend on how badly additional forage is needed on a particular portion of winter range. Certainly, more winter forage will be obtained per dollar invested on an area that has a high density of old shrubs than on an area that has only a scattering of old shrubs.

A single vigorous shrub on the Boise site produced a large proportion (74, 36, and 52 percent) of the total growth measured on the control shrubs for the years 1967, 1968, and 1969, respectively. The large twig production of this one shrub resulted in a large statistical variance for control shrubs each year, and was responsible for the failure to find significant differences between topped and control shrubs.

Retopping

In an earlier report by Ferguson and Basile (1966), the effects of topping were based upon the response of 15 topped and 15 untopped shrubs. Topping was accomplished the spring of 1960. Since 1963, occasional observations and several photographs have been made of these shrubs, but no quantitative data have been obtained. In March 1966, eight of the original topped shrubs were topped again. The new cutting was about 5 inches above the level of the original cut. During the summer of 1966, the retopped shrubs exhibited a flush of new twig growth similar to that which occurred after the first topping 6 years earlier. Figure 4 shows one of these retopped shrubs in the autumn of 1967, two growing seasons after retopping, and in July 1970, five seasons after retopping.

Longevity Following Topping

Periodic observations of the 30 shrubs involved in the 1960 trial disclosed that by July 1970 only one shrub (untopped) had died. The estimated percent dead canopy averaged 22 percent for topped shrubs and 33 percent for untopped shrubs. Thus, topping does not appear to decrease longevity of old shrubs.

Seed Production

Because topping removes one-third to one-half of the canopy from each shrub, cutting unquestionably decreases the production of seed from an old stand--and older bitterbrush shrubs often produce the largest quantities of seed. This decrease in seed production is most pronounced the first growing season after topping. From the second season on, seed production should increase rapidly, as flower buds are formed on branch wood.

Damage by Insects and Disease

There is a possibility that wounds caused by topping serve as entrance points for disease, or attract wood-destroying insects. During this 4-year study on the Boise, Modoc, and Sawtooth sites, we observed no evidence that topping encouraged either disease or insect damage.

Safety Precautions

The use of chain saws requires some safety precautions. Chain saw users should always wear protective chaps,[1] goggles, and sturdy gloves. Cutting with the top of the chain, instead of the bottom as one would be inclined to do, causes most of the debris to be thrown away from the sawyer, and also keeps the chain sprocket clean.

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[1]USDA Forest Service. Chaps, protective (for chainsaw operator), specification 6170-4a, 20 p. Northern Region, Missoula Equipment Development Center, Missoula, Montana. 1971.

Figure 4.--A, An overmature bitterbrush shrub, first topped in April 1960 and retopped March 1966. Photo (taken in November 1967) shows very good twig growth. B, in July 1970, 4 years after retopping, this shrub is still productive.

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1972. Bitterbrush topping: shrub response and cost factors, USDA Forest Serv. Res. Pap. INT-125, 11 p. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

Ten-acre stands of overmature bitterbrush (Purshia tridentata (Pursh) DC.) shrubs were topped on the Boise, Modoc, and Sawtooth National Forests. Costs of topping and the effect on annual twig production during the next four years were evaluated. The effect of topping on shrub longevity is also discussed.

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AN INVENTORY DESIGN USING STAND EXAMINATIONS FOR PLANNING AND PROGRAMING TIMBER MANAGEMENT

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ABSTRACT

Considerations guiding the design of a forest inventory for providing "in place" data for planning and programing timber management are discussed. A design is described for an inventory intended to be transitory between previous inventories that provided estimates only of forest totals and later inventories that could use a complete forest record of "in place" data. This inventory procedure uses field examination of stands in sample subcompartments augmented by aerial photo interpretation of conditions in compartments and subcompartments not examined on the ground. The data are compiled to provide timber information that can be stratified with respect to land use zones, size of stand, accessibility, land stability, productivity, and by restrictions imposed by competing uses. Estimation formulae for totals, means, and their variances are provided for the design being discussed.

INTRODUCTION

The scope of forest inventory data--its detail to support analysis of complex silvicultural alternatives, its relevance to nontimber uses of the forest, and its utility in the everyday task of implementing management plans--is changing rapidly as increasing demands for forest benefits open new options to the forest manager. The inventory design described in this report is one of several attempts to improve the data framework for effective timber management.

Specifically, we have attempted to improve the utility of the inventory for evaluating alternative land uses and management practices in these respects:

1. Describe conditions on tracts of land that are the real units of forest land management. These tracts must be small enough that analysis of the data can direct the manager's attention to specific portions of his forest for more intensive program planning. On the other hand, the tracts must have adequate detail over an area large enough to encompass those adjacent land, vegetation, and use conditions that modify or influence our management of the tract. This is our concept of the term "in place" inventory data.

2. Provide an inventory base that can support frequent revisions of plans to show changes wrought by land management activities, and to accommodate the changing multiple use status of the various tracts that results from increased knowledge of and insight into values and needs for all forest resources.

Our objective in this report is to record a procedure we have devised that incorporates these improvements and to present some of our reasons for selecting this approach from the numerous design alternatives that were considered.

PAST INVENTORY DESIGN

The precursor of this design was a two-stage approach very similar to that described in "Developing the data framework for effective timber management" (USDA Forest Serv. 1962). The first stage of the former inventory consisted of an extensive sample of about 200 ground-examined locations. At each ground location, a cluster of 10 sampling points was established to select trees for measurement. The ground samples were stratified by estimates of volume per acre as interpreted on aerial photos at a scale of 1:15,840. Stratum weights were estimated by photo interpretation of several thousand points systematically located on the aerial photos.

The second stage of the data framework consisted of examination of selected stands that had been defined on the aerial photos by discontinuities in texture (reflecting stocking and crown-size differences) or apparent tree height. The selection process at this stage was highly subjective because the purpose of the examination was to locate stands that would be likely candidates for particular programs--thinning, cleaning, overwood removal, etc. Ground examination of the stands selected used a series of sampling points along a transect within the stand.

In past practice, the timber management plan has been based entirely on the first stage inventory. Volumes of timber to be harvested and acreages of stands to be assigned various silvicultural treatments were estimated from the first stage sample. The second stage of stand examination became a procedure for verifying on the ground whether a particular treatment was indeed needed, and for presenting the manager with a limited number of alternative areas on which to assign priorities for a particular programed action based on expected costs and benefits.

There were several deficiencies in the past inventory design that limited its usefulness for intensive forest management. First, the ground sample locations described only a 1-acre portion or less of the stand in which the sampling location occurred. For several aspects of management, this area is inadequate. For example, silvicultural prescriptions based on such a limited portion of the stand often differed from the prescription that would have resulted had the entire stand been sampled, and had its relation to adjacent stands and other land-use determinants been described. For another example, the cover conditions of watersheds were inadequately described under the former design. To evaluate the impact of vegetation changes on runoff requires data that describe the forest cover in terms of the extent of stands and their spatial relations. As a final example, the ecological habitat was often inadequately classified from 10-point location data. In areas of disturbed vegetation, or where spatial variability characterizes the distribution of species, an area substantially larger than a single acre is required if the habitat classification is to be reliable. Hence, statistics compiled from widely scattered locations provided a misleading picture of the forest management opportunities.

The second major weakness was that the information from the second stage--the stand examination phase--was ignored in developing the estimates for the working circle. One reason for ignoring the stand examination data was that the detail of the measurements and their quality were not up to the standards of the first stage. Another reason was that the procedure by which stands were selected for examination provided no way to express the particular stand as a sample of the working circle. Though it would have been theoretically possible to assign examined stands to one subpopulation and the remainder of the forest area to another, there was no way to clearly define the subpopulations after stand boundaries had been obliterated by management practice. The opportunity to concentrate the second stage of stand examination on classes of stands of particular management interest (e.g., young dense stands in need of thinning) had been proposed as a desirable feature of the two-stage approach. In practice, it appears that the stand examination procedure was not a means to seek out new opportunities, but rather a means to verify the manager's existing impressions of the forest conditions.

THE REVISED DESIGN FOR SAMPLING COMPARTMENTS

In an effort to correct these deficiencies, we developed a different inventory system for trial use beginning in 1970 on two National Forests, the Coeur d'Alene in north Idaho, and the Lewis and Clark in west central Montana. Development of the system was a joint endeavor of the Northern Region and the Intermountain Forest and Range Experiment Station. While this system is new to the Northern Region, other National Forest Regions or other forest owners or managers have probably used some of the same principles or techniques.

Objectives

To support the timber management planning purpose of "providing orderly and sustained guidance for developing the timber growing capacity of working circles," we set the following specific objectives for the revised inventory design:

1. To provide "in place" data on timber management opportunities that can be stratified by land use zones, size of stand, accessibility, land stability, productivity, and by restrictions imposed by competing uses.

2. To provide "in place" data for immediate use in program development and execution.

3. To complete a timber land record system that augments the existing stand examination so as to account for all the forested acres.

4. To provide empirical information for the ecological classification of the forest into habitat types (Daubenmire and Daubenmire 1968).

5. To provide information on a stand basis that permits stands to be projected into the future, at varying intensities of management, for both inventory and management planning purposes.

6. To meet the requirements of nationwide Forest Survey and to provide inventory data compatible with other timber inventories.

Sampling Design

The revised inventory procedure is similar to its predecessor in that it uses photo interpretation of a large number of photo points to stratify the forest acreage into classes.[1] However, whereas former inventories stressed volume strata, the strata used here emphasize conditions that indicate certain opportunities for timber management. When the acreages within the strata are compiled compartment by compartment, the distribution of timber management opportunities over the entire forest, or for variously defined smaller planning units, can be compiled.

Our objectives for this inventory system emphasize the importance of examining a recognizable stand in relation to the surrounding conditions of the forest lands and their uses. This emphasis is realized by defining the ground sampling unit to be a subcompartment--the smallest permanently defined record unit suitable for long-range land management planning, including a comprehensive road system. For the Coeur d'Alene National Forest, a subcompartment encompasses an area of about 1,200 acres defined by topographic, drainage, and political boundaries. The list of 604 subcompartments and their acreages that make up the Coeur d'Alene National Forest provides a logical sampling framework for not only timber management planning inventories, but for many other kinds of inventories as well. Watershed conditions, recreational use and developmental opportunities, range condition, and many other data needs that would benefit from coordination with knowledge of timber conditions could use this same overall sampling framework.

Within the selected sample subcompartments, stands are mapped from the aerial photographs and examined on the ground using a systematic grid of plots. Each of these plots is established and data recorded exactly as they have been under the former design. The location which was sampled by a 10-point cluster under the former design, is directly analogous to the stand under the revised procedure; hence, this revised procedure should retain all the capabilities of the former design.

SELECTION OF SAMPLE SUBCOMPARTMENTS

The subcompartments to be included in the field sample were selected with probability proportional to their total National Forest land area. In other words, subcompartments were arrayed in order of size and systematically selected in such a manner that every acre on the forest had an equal chance to be included in the sample. The specific details of this procedure for drawing a randomized sample have been described by Stage (1971).

Because we had no past experience with sampling variation between subcompartments, we were "in the dark" as to the intensity of field sampling that would be needed to provide sufficient accuracy for the many kinds of analysis to which the data would be subjected. So four possible sample sizes were selected. The first sample included 21 subcompartments, distributed throughout the forest. The succeedingly larger sample sizes included the next smaller size as a subset. Thus, the sample could include 21, 28, 34, or 40 subcompartments. By selecting four possible sample sizes, we could terminate the inventory at four possible levels depending on the rate of production or the variability encountered. Even with the smallest sample, the volume estimates should meet the standards that have been specified in the past for forest-wide totals. Whether the accuracy is appropriate for the decisions to which these data relate is a question that has yet to be satisfactorily analyzed.

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[1] If facilities for easily storing, modifying, and compiling mapped information were available, this stratification could be based on stand mapping on the photos with several ensuing advantages.

In the early stages of our planning, we considered optimizing the selection of subcompartments for estimating the acreages of particular categories of stands. In effect, this procedure would have resulted in as many independent, optimized inventories as there were categories of stands. Such a procedure would be desirable if the stands *not* of the category for which the subcompartment had been selected could be ignored.

We rejected this approach because the stand boundaries between categories are not always clearly defined nor would they be drawn in advance of the selection of subcompartments for examination. Thus, any bias generated by special attention to a category in drawing the boundaries would result in bias in the final estimates of the population totals.

Consequently, we decided to sample *all* stands in each selected subcompartment. By so doing, any shift in stand boundaries would *not* affect the estimates of the population totals, although the acreages in particular categories would reflect any net bias in the drawing of their boundaries.

To illustrate the distinction between these two alternatives, consider a hypothetical subcompartment consisting of two stands classified into different strata. If the expansion factor for a unit of land area sampled in one stand is the same as that for a sample in the other stand, then shifting the boundary between stands can only increase the average volume per acre (or of any other character) of one stratum at the expense of the other stratum. Consequently, the net effect on the estimate of the population total is zero. However, if the expansion factors of the two stand categories differed as they would if the sampling intensity were varied so as to optimize the independent inventories, then there would be no guarantee that the shift in boundaries would be compensating in its effect on the population total.

Moreover, including all stands in the management unit enhances our capability to consider the limitations or opportunities imposed by adjacent stand conditions.

We would like to emphasize that our reservations about sampling stands using unequal probabilities would disappear if we had the capability to map all stands in all compartments in advance of the sample selection. Forthcoming modifications of this design will, we hope, utilize complete stand mapping.

PHOTO SAMPLING PROCEDURE

The aerial photo phase of the inventory is accomplished using resource photography of 1:15,840 scale (4 inches per mile). Photo interpretation assigned stands (or nonstocked areas) within the selected subcompartments and grid points on the remaining area into one of 11 strata. These strata are defined on page 7. Stand boundaries are defined by discontinuities in stand height, stand texture, or crown closure. The stand is subordinate to the stratum, so that stand boundaries do not cross stratum boundaries.

Within each subcompartment selected for field sampling, all stands are delineated on the photos to a 10-acre minimum size. Their acreages are determined either by planimeter, or by counting the ground plots that fall within the stand boundary.

On the remaining portions of the forest, an overlay grid is superimposed on alternate photos to establish photosample points. The spacing of the grid points is such that each point represents about 100 acres. The interpreter then classifies the stand in which the grid point is located (not just the condition at the point) into one of the 11 strata. Along with the known acreage of the compartment, the proportion of points in a stratum establishes the stratum area.

Definition of photo interpretation strata used in 1970 inventory on the Coeur d'Alene and the Lewis & Clark National Forests[1]

Stand Height Greater Than 40 Feet

Code	Crown Cover Description	Crown Cover Texture
21	Medium and well stocked	Coarse[2]
22	Medium and well stocked	Fine
23	Poorly stocked	Coarse
24	Poorly stocked	Fine
25	Two storied--overstory with manageable understory Overstory generally poor but no more than medium stocked Understory poorly (or more) stocked: at least 100 trees per acre would be left after removing overstory	

Stand Height Less Than 40 Feet

26	Medium and well stocked	Fine texture
27	Poorly stocked	Fine texture
28	Apparently nonstocked	

Other

40	Noncommercial forest
60	Nonforest
92	Water (noncensus)

[1]This scheme for stand classification on aerial photos was devised by C. W. Brown, Northern Region, USDA Forest Service.

[2]Texture is a visual interpretation of the impression given by variability of crown size.

In addition to the timbered characteristics of each photo point, the following attributes are recorded:

a. Multiple Use Zone and Key Value

b. Special Study Area Classification

c. Soil Stability Class

d. Geographic Identity (subcompartment)

e. Ecological Habitat Type

Estimates of the acreages of the 11 strata occurring within a particular land management unit--whether it be a Ranger District, a compartment, or any geographic area of special interest--will be computed from the proportions of the photo points falling in the respective strata.

GROUND SAMPLING PROCEDURE

A referenced base line is laid out through each selected subcompartment. The base line provides starting points for line-plot sampling of the entire subcompartment. Starting points along the base line are established for permanency and referenced for remeasurement. Transects are run perpendicularly to the base line at intervals of 10 chains horizontal distance. Plots along the transects are spaced at 5-chain intervals. This frequency provides a sample point for each 5 acres of area. All plots are referenced to the stand in which they occur as delineated on the photos. Figure 1 is a schematic diagram of the grid layout.

The inventory field procedure at each point is similar to individual points in the 1-acre 10-point cluster system. Some features of this procedure are:

a. A fixed plot 1/300 acre in size for recording trees less than 5 inches d.b.h.

b. A variable plot for recording trees 5.0 inches and larger.

c. Azimuth recorded to each tree over 5.0 inches d.b.h.

d. Each tree over 3.0 inches d.b.h. tagged.

e. On nonstocked areas, satellite plots (1/300 acre) are taken 1/2 chain ahead, 1/2 chain back, and 1/2 chain perpendicularly to each side of the principal point of the transect. Variable plots are only taken at the principal plot location.

In addition to the typical tree data normally recorded on the plot that provide volume and condition information, inventory crews record the ecological situation as represented by vegetative indicators. We are using the Daubenmires' (1968) habitat type classification for north Idaho and eastern Washington. The inventory classification of habitat type will permit us to develop criteria for mapping the entire forest by habitat types.

NET VOLUME SUBSAMPLING PROCEDURE

Since 1964, net volume has been estimated in the Northern Region using a destructive subsampling procedure. This procedure of dissecting felled trees provides adjustment factors for three sources of error in estimates of net volume: (1) volume tables; (2) cull and defect allowances; and (3) inaccurate height estimation.

The subsample has been comprised of randomly selected locations. Under the new approach, the same procedure will be followed by drawing the subsample from the 215 locations established in the preceding inventory of 1961-62. Although the remeasurement of these sample plots will provide useful data on growth and mortality in addition to volume-table and cull and defect allowances, it will not provide control of measurement error in the current inventory. Accordingly, the destructive sampling will extend to a subsample of the points being established in the subcompartments of the current inventory.

The field procedures for the destructive sample and subsequent net tree volume calculations are described by Stage and others (1968).

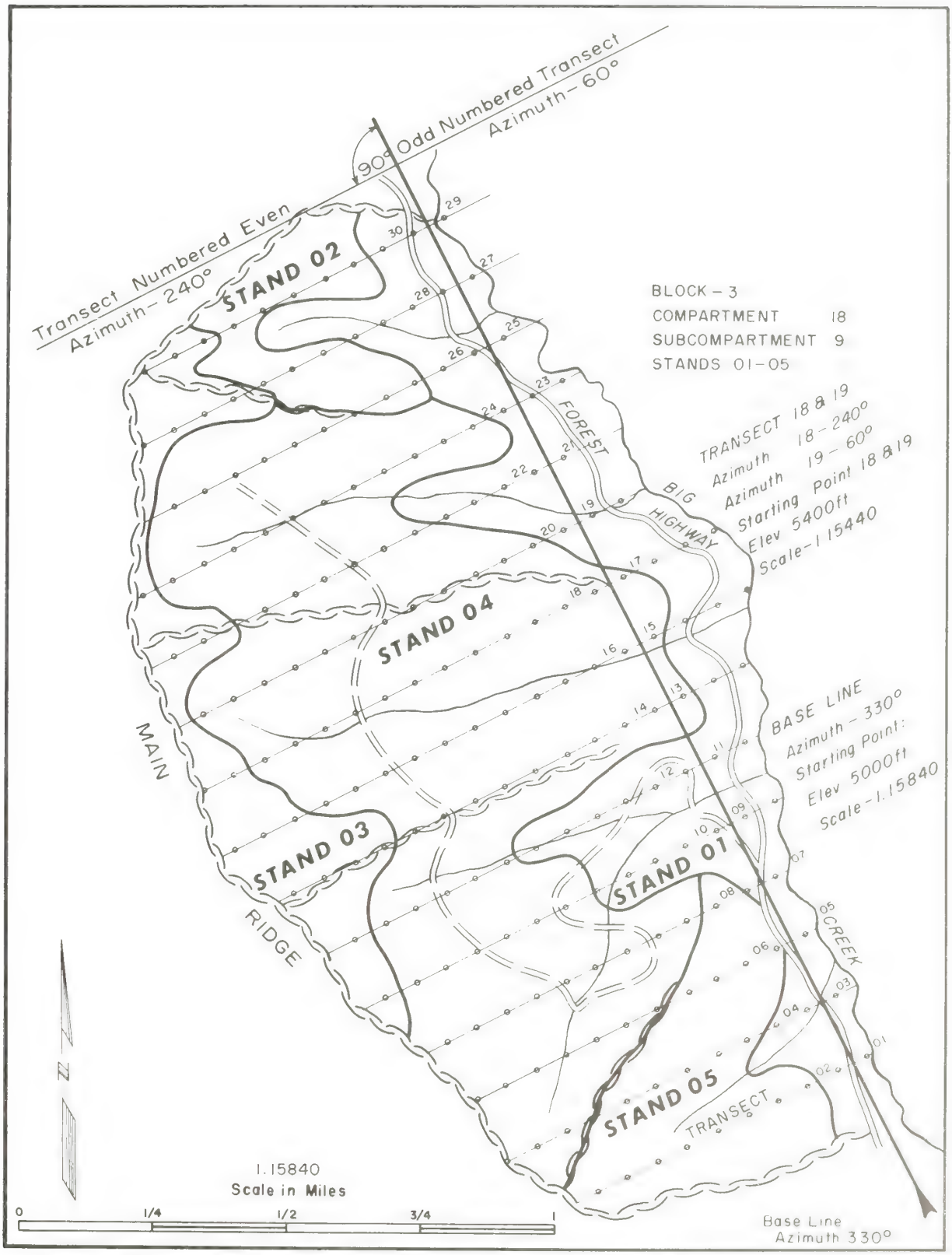


Figure 1.--Diagrammatic layout of a stand showing transect lines, compartments, and sampling points.

Remeasurement

Permanent field locations established by this inventory lend themselves to remeasurement. However, several considerations should govern the reinventory design. First, reinventories based to a large degree on repeated examination of the same sample locations will perpetuate deviations about the true population total. This persistence is particularly serious when the programed level of harvest is one of the population totals being estimated. The feedback effect of remeasured plots in inventories for harvest scheduling has not been examined thoroughly. However, there exists a definite possibility that the serial correlation of sampling errors from inventory to reinventory could result in persistent overcutting, undercutting, or unstable, destructive oscillations that would vitiate our reliance on compensating corrections as a result of successive revision of the management plan.

The second consideration is that the availability of "in place" information will play a major role in timber management program development during the execution of the plan. In other words, the timber programs will tend to be concentrated in the hundreds of stands already inventoried on the ground. Therefore, at the time of reinventory, those subcompartments already inventoried on the ground will have to be treated as one stratum, those not already inventoried on the ground as another stratum.

In summary, the design discussed in this paper should be considered a transitional design for establishing a complete timberland record based on stand examinations. Subsequent inventories for the same forest should be designed to use the information contained in these records so as to provide statistically sound estimates of the current forest situation with greatly increased efficiency.

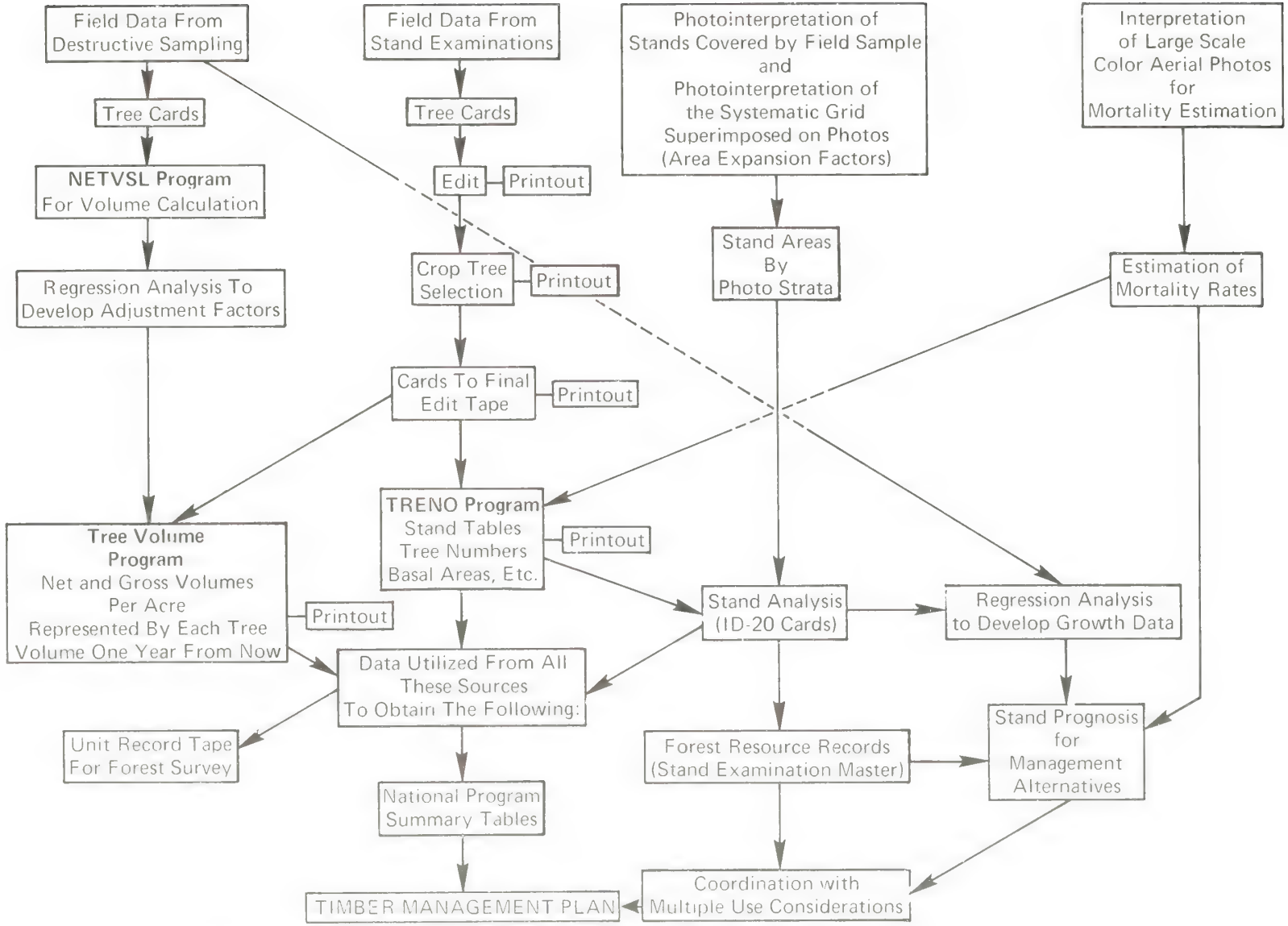
Compilation

Compilation procedures are quite similar to those used in processing typical random plot inventory data, the major change being development of "stand" data rather than "plot" or "location" data. The only real change in compilation procedures is to replace the constant 10 for points per cluster with a variable number of points per stand. Variance estimates are, of course, quite different. Variance computations are described on page 15. An abbreviated flow chart is included in figure 2 to illustrate data flow and the correlation of the four major types of information--the field inventory, the photo inventory of stands, photo mortality samples, and the felled-tree (net volume) data.

The first stage of the output that is of use to the forest manager is the stand analysis. These stand records are the basic material from which the management program is built. In particular, growth prognoses under alternative stand treatments can be used to develop a rational basis for establishing the management program.

It should be emphasized at this point that stand or "in place" data developed by field inventory in this overall system lose considerable utility unless the forest manager has an information system that provides ready storage and retrieval of individual stand data.

The various stand attributes are averaged within their respective strata. These stratum means are inferred to the nonsampled acres within the strata by compartments. Thus, the photo classification phase of the double-sampling procedure will extend the stand data to those compartments not sampled on the ground. Compartments average about 5,700 acres in size, so there will be about 57 photo samples in each. Compartment statistics determined solely from photo stratification will fill in the gaps in the inventory of the entire forest. As additional field inventory work (stand examination) is completed in ensuing years, it will replace information based on only strata means. The summary of these compartment records provides the final stage of the output. This output consists of a series of tables that provides the base for broad scale timber management planning.


Field Data From Destructive Sampling
Field Data From Stand Examinations
Photointerpretation of Stands Covered by Field Sample and Photointerpretation of the Systematic Grid Superimposed on Photos (Area Expansion Factors)
Interpretation of Large Scale Color Aerial Photos for Mortality Estimation
Tree Cards
Tree Cards
NETVSL Program For Volume Calculation
Edit
Printout
Stand Areas By Photo Strata
Crop Tree Selection
Printout
Estimation of Mortality Rates
Regression Analysis To Develop Adjustment Factors
Cards To Final Edit Tape
Printout
TRENO Program Stand Tables Tree Numbers Basal Areas, Etc.
Printout
Tree Volume Program Net and Gross Volumes Per Acre Represented By Each Tree Volume One Year From Now
Printout
Stand Analysis (ID-20 Cards)
Regression Analysis to Develop Growth Data
Data Utilized From All These Sources To Obtain The Following:
Unit Record Tape For Forest Survey
Forest Resource Records (Stand Examination Master)
Stand Prognosis for Management Alternatives
National Program Summary Tables
Coordination with Multiple Use Considerations
TIMBER MANAGEMENT PLAN

SAMPLE ESTIMATING FORMULAE

We wish to emphasize the development of estimates for compartments and subcompartments, with forest totals developed from sums over the smaller subpopulations. Accordingly, the following expressions will differ slightly from those that might be derived solely for forest totals.

Summaries of Tree Characteristics Within Stands

Let {character} be any characteristic of the sample unit that is being summarized. At the tree level, it could be the volume of the tree or any portion of it. If number of trees per acre is the item of interest, then {character} would be unity at the tree level. To obtain breakdowns by species, or tree class, {character} would be defined only for the species or class being summarized and zero otherwise.

n_k = number of points in stand "k"

c_{kj} = {character} of jth tree in stand "k"

g_{kj} = basal area of the jth tree in stand "k"

C_{ik} = total of {character} per acre of the kth stand in subcompartment "i"

baf = basal area factor for point sampling (sq.ft./tree)

fpa = fixed plot area (acres)

$$C_{ik} = \frac{1}{n_k} \sum_j \frac{c_{kj}}{f_{kj}} \tag{1}$$

where

$$f_{kj} = \begin{cases} \dfrac{g_{kj}}{\text{baf}} \text{ if dbh } \geq 5 \text{ in.} \\ \text{fpa if dbh } < 5 \text{ in.} \end{cases}$$

Summaries of Stand Characteristics in Subcompartments Selected for Ground Examination

A_{ik} = area of the kth stand in subcompartment "i"

$$\delta_{hik} = \begin{cases} 1 \text{ if } k\text{th stand in subcompartment "}i\text{" is in the photo stratum "}h\text{"} \\ 0 \text{ if not in that stratum} \end{cases}$$

TVA_{hi} = total of {character} per acre in the subcompartment "i" for only those stands in photo stratum "h"

$$M_{hi} = \frac{\sum_k A_{ik}\,\delta_{hik}}{\sum_k A_{ik}}$$ = proportion of area of subcompartment "i" that is in the "h" stratum

$$TVA_{h\cdot} = \frac{\sum_k \quad}{\sum_i}$$ (2)

Note that the denominator is proportional to the total acreage of stratum "h" in subcompartment "i." If acres by management class are the feature being compiled, C_{ij} would be unity for stands in that class and zero otherwise.

Stratum Means

An estimate for stratum means will be developed first for the general case in which subcompartments are selected with arbitrary probabilities. The simplification that results from defining the selection probability to be proportional to acres in the subcompartment will then be demonstrated.

Let P_i be N times the probability that subcompartment "i" would be drawn for any any one of the N sample units. Then $\sum_i P_i = N$ where "i" ranges over all subcompartments in the forest. The expression for the stratum mean is then:

$$\overline{TVA}_h = \frac{\sum_i TVA_{hi} M_{hi} \sum_k A_{ik}/P_i}{\sum_i \quad \sum_k}$$ (3)

Expression (3) is a fraction in which the numerator is an estimate of the total {character} in stratum "h." The denominator is the corresponding estimate of the area in the stratum. Because both numerator and denominator are estimated using the same sampling units, their covariance should help to reduce the variance of the ratio. If P_i is defined to be proportional to the total forest acreage in the ith subcompartment ($\sum_k A_{ik}$), then (3) reduces to:

$$\overline{TVA}_h = \frac{\sum_i TVA_{hi} \cdot M_{hi}}{\sum_i M_{h\cdot}}$$ (4)

If the proportions M_{hi} are established from absolute measures of acreage of each stand, then (3) can also be expressed as:

$$\overline{TVA}_h = \frac{\sum_i TVA_{hi} \sum_k a_{ik}\delta_{hik}/P_i}{\sum_i \sum_k A_{ik}\delta_{hik}/P_i}$$ (3a)

Likewise, an expression exactly equivalent to (4) can be obtained by omitting the value of P_i from (3a).

Totals for Compartments

CT_p = compartment total of {character} in all strata

F_{hp} = count of photo points in stratum "h" in compartment "p" (exclusive of ground-sampled subcompartments)

X_p = acres of forest land in compartment "p" (exclusive of ground-sampled acreage)

$$CT_p = \sum_h X_p \frac{F_{hp}}{\sum_l F_{lp}} \cdot \overline{TVA}_h + \sum_i TVA_{hi} \sum_k A_{ik}\, \delta_{hik} \qquad (5)$$

In expression (5), i ranges over only the sampled subcompartments within compartment "p."

Forest Totals

Combining all the preceding estimation formulae into an estimate of the forest grand total (FGT),

$$FGT = \sum_p \sum_h \overbrace{X_p \frac{F_{hp}}{\sum_l F_{lp}}}^{W} \overbrace{\frac{\sum_i M_{hi} \dfrac{\sum_k \delta_{hik} \sum_j c_{kj}/f_{kj}}{\sum_k n_k\, \delta_{hik}}}{\sum_i M_{hi}}}^{\overline{TVA}_h} + \sum_i TVA_{hi} \sum_k A_{ik}\, \delta_{hik} \qquad (6)$$

where

j indexes individual trees

k indexes the stands

i indexes the subcompartments

p indexes the compartments

h, l index the strata

For purposes of error calculation, there are two random variables in the sampling procedure. These are designated W and $\overline{TVA}_h$ in expression (6).

W is the estimated stratum weight. The expression for the variance of FGT must include a component arising from W because it is an estimate that is subject to sampling variation. The usual derivations of variance-estimating formulae for two-stage sampling plans assume that the stratum weights follow a multinomial distribution. In the design we have described, the systematic nature of the photo-point grid will result in estimates having somewhat lower variance. Williams (1956) has demonstrated how the variance of the mean of systematic samples such as these can be evaluated. However, the planned spacing between photo points in the compartments is large enough that the correlation between strata identified at points separated by 4/10 mile should be quite low. Accordingly, the multinomial distribution should be a reasonable basis for evaluating the variance of the first-stage sample of stratum weights.

The second random variable ($\overline{TVA}_h$) is the estimate of stand characters for the stratum: volume per acre, excess trees per acre, silvicultural prescription, or whatever is the character associated with a sampling point in the subcompartments selected for ground examination. For purposes of assessing the variance of the stand estimates, the mean square deviation from the stand average is pertinent. However, for assessing the variance of the forest summaries over the compartments, it should be recognized that $\overline{TVA}_h$ is the ratio of two random variables.

Compartment Variances

The variance computations can best be illustrated by considering the compartment estimates on a per-acre basis:

$$\bar{Y}_h = \frac{\sum_i M_{hi} \bar{y}_{hi}}{\sum_i M_{hi}}$$

To simplify notation and to facilitate cross-reference to standard sampling texts such as Cochran (1963), let

n_{hi} = number of sample points in stratum "h" in subcompartment "i"

$\bar{y}_{hi} = \sum_k y_{hik}/n_{hi}$

$\bar{z}_{hi} = \sum_k z_{hik}/n_{hi}$

$y_{hi} = M_{hi}\,\bar{y}_{hi} = \sum_k y_{hik}$

$z_{hi} = M_{hi}\,\bar{z}_{hi} = \sum_k z_{hik}$

$\bar{Y}_h = \sum_i M_{hi}\,\bar{y}_{hi} / \sum_i M_{hi} = \sum_i y_{hi} / \sum_i M_{hi}$.

That is, $\bar{Y}_h$ and $\bar{Z}_h$ are numerator and denominator of $\overline{TVA}_h$ respectively. Denote the variance of their ratio by

$$v_h = \text{Var}\,(\bar{Y}_h/\bar{Z}_h).$$

The variance of such a ratio can be approximated by the relation

$$v_h = \left(\frac{\bar{Y}_h}{\bar{Z}_h}\right)^2 \left(\frac{\text{Var}\,(\bar{Y}_h)}{\bar{Y}_h^2} + \frac{\text{Var}\,(\bar{Z}_h)}{\bar{Z}_h^2} - \frac{2\,\text{Cov}\,(\bar{Y}_h,\bar{Z}_h)}{\bar{Y}_h \bar{Z}_h}\right)$$

With clustered samples such as are used in this design, the variance depends on the mean-square deviation of the subcompartment means ($\bar{Y}_h$,$\bar{Z}_h$) about the corresponding mean for the forest. This mean-square deviation includes two components of variation: (1) the variance between subcompartments, and (2) the contribution from the sampling within the subcompartment that yields an estimate of the mean that differs from the true and unknown mean for that subcompartment.

To illustrate the computation of the appropriate mean-square deviation, the formula for Cov $(\bar{Z}_h, \bar{Y}_h)$ will be used. The corresponding formulae for Var $(\bar{Y}_h)$ or Var $(\bar{Z}_h)$ are obvious by recalling that Var $(\bar{Y}_h)$ = Cov $(\bar{Y}_h, \bar{Y}_h)$.

$$\text{Cov } (\bar{Y}_h, \bar{Z}_h) = \frac{1}{N-1} \left[N \sum_{i=1}^{N} (Y_{hi} Z_{hi} / P_i^2) - \bar{Y}_h \bar{Z}_h \right] \tag{8}$$

A sample estimate of the variance for double sampling designs is computed from an approximation given by Cochran (1963, p. 333). Let

$T_p = \sum_h F_{hp}$ = total photo-interpreted points in compartment "p"

$CA_p = \sum_h F_{hp} \overline{TVA}_h / T_p$ = average of {character} per acre in compartment "p"

Then

$$\widehat{\text{var}} \ (CT_p) \doteq \frac{X_p^2}{T_p^2 - T_p} \sum_h \left[(F^2_{hp} + F_{hp}) \ S^2_h + F_{hp} \ (\overline{TVA}_h - CA_p)^2 \right] \tag{9}$$

The finite population correction designated as g' by Cochran has been omitted in expression (9) because the sampling, although usually systematic, should be considered as occurring with replacement. As discussed previously, obtaining F_{hp} from a systematic sample will cause the variance estimate above to be too large if the interpretation points are so close together that their serial correlation is substantial.

The variance estimate (9) assumes that the stratum areas are estimated by the same sampling intensity in all compartments. For those compartments containing subcompartments for which stratum areas can be determined more exactly, it would seem reasonable to determine the total areas from the sums of the known areas (dividing by acres per photo point) plus the usual sample of photo points for the remainder. Generally, this combination of areas will provide a more accurate estimate, although the variance computation will not show the improvement.

The variance of the grand totals can be calculated as the sum of the compartment variances. Forest totals could be estimated somewhat more precisely if counts of photo points and acres were totaled over the compartments first and these totals used in place of X_p, T_p, and F_{hp} in the formulae for the compartment total and its variance. However, an important feature of this inventory design is its capability for including the results of additional stand examinations as they are accomplished. These additional data will be entered at the compartment record level. Hence, compilation procedures will be more easily handled if totals and variances are aggregated upward from that level.

In a similar way, statistics for various combinations of compartments can be compiled readily by adding totals and variances for the included compartments.

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1972. An inventory design using stand examinations for planning and programing timber management. USDA Forest Serv. Res. Pap. INT-126, 17 p., illus. Intermountain Forest and Range Experiment Station, Ogden, Utah, 84401.

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